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Measurement of the production cross section for W -bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector[☆]

ATLAS Collaboration^{*}

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ABSTRACT

This Letter reports on a first measurement of the inclusive W + jets cross section in proton–proton collisions at a centre-of-mass energy of 7 TeV at the LHC, with the ATLAS detector. Cross sections, in both the electron and muon decay modes of the W -boson, are presented as a function of jet multiplicity and of the transverse momentum of the leading and next-to-leading jets in the event. Measurements are also presented of the ratio of cross sections $\sigma(W + \geq n)/\sigma(W + \geq n - 1)$ for inclusive jet multiplicities $n = 1$ –4. The results, based on an integrated luminosity of 1.3 pb^{-1} , have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics. The measured cross sections are compared to particle-level predictions based on perturbative QCD. Next-to-leading order calculations, studied here for $n \leq 2$, are found in good agreement with the data. Leading-order multiparton event generators, normalized to the NNLO total cross section, describe the data well for all measured jet multiplicities.

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1. Introduction

The study of massive vector boson (V , where $V = W$ or Z) production in association with one or more jets (V + jets) is an important test of quantum chromodynamics (QCD). In addition, V + jets processes are a significant background to studies of Standard Model processes such as $t\bar{t}$ or single-top production, as well as searches for the Higgs boson and for physics beyond the Standard Model. Measurements of the cross section and kinematic properties of V + jets processes and comparisons to theoretical predictions are therefore of significant interest. This Letter reports on a first measurement at the Large Hadron Collider (LHC) of the W + jets cross section in proton–proton (pp) collisions at a centre-of-mass energy (\sqrt{s}) of 7 TeV, in both electron and muon decay modes of the W -boson, with the ATLAS detector. The measurement is based on an integrated luminosity of approximately 1.3 pb^{-1} .

The cross section measurements are presented as a function of jet multiplicity and of the transverse momentum (p_T) of the leading and next-to-leading jets in each event. Measurements are also presented of the ratio of cross sections $\sigma(W + \geq n)/\sigma(W + \geq n - 1)$ for inclusive jet multiplicities $n = 1$ –4. The results have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics, fully covered by the detector acceptance, so as to avoid model-dependent extrapolations and to facilitate comparisons with theoretical pre-

dictions. Previous measurements of W + jets production in proton–antiproton collisions at $\sqrt{s} = 1.96$ TeV were published by the CDF Collaboration [1]. Theoretical calculations at next-to-leading-order (NLO) in perturbative QCD (pQCD) have been computed for up to four jets for W production [2,3]. Comparisons are made in this Letter with NLO pQCD calculations for $n \leq 2$; higher jet multiplicities are compared only to leading-order (LO) calculations.

2. The ATLAS detector

The ATLAS detector [4,5] consists of an inner tracking system (inner detector, or ID) surrounded by a thin superconducting solenoid providing a 2T magnetic field, electromagnetic and hadronic calorimeters and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip (SCT) detectors, surrounded by the transition radiation tracker (TRT). The electromagnetic calorimeter is a lead liquid-argon (LAr) detector. Hadron calorimetry is based on two different detector technologies, with scintillator-tiles or LAr as active media, and with either steel, copper, or tungsten as the absorber material. The MS is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, and a system of three stations of chambers for the trigger and for precise measurements. The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive x -axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y -axis pointing upwards, while the beam direction defines the z -axis. The azimuthal angle ϕ is measured around the beam axis and

[☆] © CERN, for the benefit of the ATLAS Collaboration.^{*} E-mail address: atlas.publications@cern.ch.

the polar angle θ is the angle from the z -axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$.

3. Simulated event samples

Simulated event samples were used for most of the background estimates, for the correction of the signal yield for detector effects and for comparisons of the results to theoretical expectations. The detector simulation [6] was performed using GEANT4 [7]. The simulated event samples are summarised in Table 1. The ALPGEN samples were generated with the MLM matching scheme [8] and interfaced to HERWIG v6.510 [9] for parton shower and fragmentation processes and to JIMMY v4.31 [10] for underlying event simulation. Parton density functions (PDF) were: CTEQ6L1 [11] for the ALPGEN and SHERPA samples, MRST 2007 LO* [12] for PYTHIA, and MSTW2008 [13] for FEWZ [14]. For the POWHEG samples, the PDF set was CTEQ6.6M [15] for the NLO matrix element calculations, while CTEQ6L1 was used for the parton showering and underlying event via the POWHEG interface to PYTHIA. The radiation of photons from charged leptons was treated in HERWIG and PYTHIA using PHOTOS v2.15.4 [16]. TAUOLA v1.0.2 [17] was used for tau decays. The underlying event tune was the ATLAS MC09 tune [18] for the ALPGEN samples, PYTHIA inclusive vector boson production, and PYTHIA QCD samples. The POWHEG sample used the ATLAS MC09 tune with one parameter adjusted.¹ The AMBT1 [19] tune was used for the PYTHIA W + jets samples. The samples generated with SHERPA used the default underlying event tune. Samples were generated with minimum bias interactions overlaid on top of the hard-scattering event in order to account for the multiple pp interactions in the same beam crossing (pile-up) experienced in the data. The number of minimum bias interactions followed a Poisson distribution with a mean of two [20]. These samples were then reweighted such that the distribution of the number of primary vertices matched that of the data.

4. Data and event selection

The data used in this analysis were collected from March to August 2010. Application of beam, detector, and data-quality requirements resulted in a total integrated luminosity of 1.3 pb^{-1} . The uncertainty on the luminosity determination is estimated to be 11% [26]. Criteria for electron and muon identification, as well as for event selection, followed closely those for the W -boson inclusive cross section analysis [27].

In the electron channel, a hardware-based level-one trigger system selected events containing one or more electron candidates, based on the presence of a cluster in the electromagnetic calorimeter with a transverse energy (E_T) greater than 14 GeV; this is the only difference in the electron channel with respect to the W inclusive cross section analysis, and was motivated by the fact that, for this larger dataset, this trigger was the lowest-threshold, useful electromagnetic trigger without any additional higher-level trigger requirements. The impact of the trigger efficiency was negligible for electrons with $E_T > 20 \text{ GeV}$. In the offline analysis, electrons were required to pass the standard “tight” electron selection criteria [27] with $E_T > 20 \text{ GeV}$ and $|\eta| < 2.47$; electrons in the transition region between the barrel and endcap calorimeter ($1.37 < |\eta| < 1.52$) were rejected. The “tight” selection was used in order to improve the rejection of the QCD background. No isolation requirement was applied to the electron selection. Events were also rejected if there was a second electron passing the “medium”

electron selection criteria [27] and the same kinematic selections as above.

In the muon channel, the hardware-based trigger selected events containing one or more muon candidates, based on hit patterns in the MS, corresponding to $p_T > 10 \text{ GeV}$. Offline, the muons were required to be identified in both ID and MS sub-systems and to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$. The ID track was required to have ≥ 2 hits in the pixel detector, ≥ 6 hits in the SCT and, for tracks with $|\eta| < 2.0$, ≥ 1 hit in the TRT. The muon impact parameter with respect to the primary vertex [20] was required to be $< 0.1 \text{ mm}$ and $< 10 \text{ mm}$ in the r - ϕ and r - z planes, respectively. The first of these requirements was added to further reduce non-prompt muons from decays of hadrons, and muons from cosmic rays. The difference between the ID and MS p_T , corrected for the mean energy loss in upstream material, was required to satisfy $|p_T^{\text{ID}} - p_T^{\text{MS}}| < 0.5 \times p_T^{\text{ID}}$. Compared to the criteria used in Ref. [27], this scaled requirement reduced the background from decays-in-flight of hadrons and improved the signal efficiency at high p_T . As in Ref. [27], the muons were required to be isolated, following a track-based isolation, but the cone size was reduced from $\Delta R = 0.4$ to $\Delta R = 0.2$ (where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of the muon) and the isolation requirement was changed from $\Sigma p_T^{\text{ID}}/p_T < 0.2$ to $\Sigma p_T^{\text{ID}} < 1.8 \text{ GeV}$ to improve the QCD background rejection. With these optimised cuts, the QCD background was reduced by a factor of 1.7 for the inclusive 1-jet sample. In addition, a number of requirements were added on the tracks inside the isolation cone: the difference between the z position of the track extrapolated to the beam line and the z coordinate of the primary vertex was required to be $< 1 \text{ cm}$, and the total number of hits in the pixel and SCT detectors was required to be ≥ 4 . These additional requirements further improved the rejection of QCD background. Events were rejected if there was a second muon passing the same kinematic selections and isolation requirements as above.

The calculation of missing transverse energy (E_T^{miss}) and transverse mass (M_T) followed the prescription in Ref. [27]. M_T was defined by the lepton and neutrino p_T as $M_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$, where the (x, y) components of the neutrino momentum were inferred from the corresponding E_T^{miss} components. E_T^{miss} was calculated from the energy deposits of calorimeter cells inside three-dimensional clusters [28]. These clusters were then corrected to take into account the different response to hadrons compared to electrons or photons, as well as dead material and out-of-cluster energy losses [29]. In the muon channel, E_T^{miss} was corrected for the muon momentum. Events were required to have $E_T^{\text{miss}} > 25 \text{ GeV}$ and $M_T > 40 \text{ GeV}$. After requiring ≥ 1 primary vertex with ≥ 3 associated tracks in the event, the primary vertex was required to be within 150 mm along the beam direction relative to the centre of the detector. In events with multiple vertices along the beam axis, the vertex with the largest Σp_T^2 of associated tracks was taken as the primary event vertex. Starting from approximately 9.6×10^6 triggered events in each of the electron and muon channels, these selection criteria reduced the sample to 4216 and 4911 events, respectively.

Jets were reconstructed using the anti- k_t algorithm [30] with a radius parameter $R = 0.4$ [31]. The efficiency for reconstructing jets was found to be approximately 98% in simulation for jet p_T of 20 GeV, rising to close to 100% efficiency for 30 GeV jets. Jets arising from detector noise or cosmic rays were rejected [32]. To take into account the differences in calorimeter response to electrons and hadrons, a p_T - and η -dependent factor, derived from simulated events, was applied to each jet to provide an average energy scale correction [31] back to particle-level. Jets were required to have $|\eta| < 2.8$ and $p_T > 20 \text{ GeV}$. All jets within $\Delta R < 0.5$ of an

¹ The cutoff for multiple parton interactions, PARP(82), was adjusted from 2.3 to 2.1 GeV, suitable for the CTEQ6L1 PDF.

Table 1

Signal and background simulated event samples used in this analysis, including the production cross section (multiplied by the relevant branching ratio, BR). The variable \hat{p}_T is the average p_T of the two outgoing partons involved in the hard-scattering process, evaluated before modifications from initial- and final-state radiation and from the underlying event. The W inclusive cross section is given at next-to-next-to-leading-order (NNLO), the $t\bar{t}$ cross section is given at next-to-leading-order (plus next-to-next-to-leading-log, NNLL), and the dijet cross sections are given at leading-order (LO) in pQCD. The W + jets and Z + jets samples were normalised using the inclusive cross sections. For PYTHIA, the inclusive W sample is based on a $2 \rightarrow 1$ matrix element merged with a $2 \rightarrow 2$ matrix element and a leading-logarithmic parton shower; the W + jets samples are based on $2 \rightarrow 2$ matrix elements. Details of PDF sets, final-state photon radiation, and underlying event tunes are given in the text.

Physics process	Generator	$\sigma \cdot \text{BR}$ (nb)		
$W \rightarrow \ell \nu$ inclusive ($\ell = e, \mu, \tau$)	PYTHIA 6.4.21 [21]	10.46	NNLO	[14]
$W^+ \rightarrow \ell^+ \nu$		6.16	NNLO	[14]
$W^- \rightarrow \ell^- \bar{\nu}$		4.30	NNLO	[14]
$W \rightarrow \ell \nu$ + jets ($\ell = e, \mu, \tau$)	PYTHIA 6.4.21 [21]			
$W \rightarrow \ell \nu$ + jets ($\ell = e, \mu, \tau, 0 \leq N_{\text{parton}} \leq 5$)	ALPGEN 2.13 [22]			
$W \rightarrow \ell \nu$ + jets ($\ell = e, \mu, \tau, 0 \leq N_{\text{parton}} \leq 4$)	SHERPA 1.1.3 [23]			
$Z \rightarrow \ell \ell$ + jets ($m_{\ell\ell} > 40$ GeV, $0 \leq N_{\text{parton}} \leq 5$)	ALPGEN 2.13 [22]	1.07	NNLO	[14]
$t\bar{t}$	POWHEG-HVQ v1.01 patch 4 [24]	0.16	NLO + NNLL	[25]
Dijet (e channel, $\hat{p}_T > 15$ GeV)	PYTHIA 6.4.21 [21]	1.2×10^6	LO	[21]
Dijet (μ channel, $\hat{p}_T > 8$ GeV, $p_T^\mu > 8$ GeV)	PYTHIA 6.4.21 [21]	10.6×10^6	LO	[21]

electron or muon (that passed the lepton identification requirements) were removed, regardless of the jet p_T or η .

Jets from pile-up interactions were removed by a cut on the jet-vertex fraction (JVF) which was computed for each jet in the event. After associating tracks to jets with a simple matching in $\Delta R(\text{track}, \text{jet})$, requiring $\Delta R < 0.4$, the JVF was computed for each jet as the scalar sum p_T of all matched tracks from the primary vertex divided by the total jet-matched track p_T from all vertices. Jets which fell outside of the fiducial tracking region ($|\eta| < 2.5$) or which had no matching tracks were not considered for the JVF cut. Jets for which $JVF < 0.75$ were rejected; this requirement was chosen to optimise the Kolmogorov distance between the jet multiplicity (in data) with and without pile-up interactions. The application of the JVF cut reduced the sensitivity of the measured jet multiplicity distribution to additional jets from pile-up. The rejection rate of pile-up jets was found to be linear as a function of the number of pile-up interactions. The bias of the JVF cut on the jet multiplicity was found to be negligible for events with ≤ 4 jets.

5. Signal and background yields

The major background processes in the electron channel are QCD and leptonic backgrounds. The latter consist of $W \rightarrow \tau \nu$ where the tau decays to an electron, $Z \rightarrow ee$ where one electron is not identified and hadronic energy in the event is mismeasured, and semileptonic $t\bar{t}$ decays ($t\bar{t} \rightarrow b\bar{b}q\bar{q}'e\nu$). The QCD background in the electron channel has two components, one where a hadronic jet passes the electron selection and additional energy mismeasurement in the event results in large E_T^{miss} , and the other where a bottom- or charm-hadron decays to an electron. For the muon channel, the main backgrounds arise from semileptonic heavy flavour decays in multijet events and from the leptonic background from the following sources: $W \rightarrow \tau \nu$ where the tau decays to a muon, $Z \rightarrow \mu\mu$ where one muon is not identified, and semileptonic $t\bar{t}$ decays in the muon channel. The contributions of single-top and diboson production to the measured cross section have been estimated to be slightly smaller than the $W \rightarrow \tau \nu$ background, and are not subtracted from the data.

The number of leptonic background events surviving the above selection cuts was estimated with simulated event samples: ALPGEN for vector boson samples (PYTHIA was used for $W \rightarrow \tau \nu$ + jets) and POWHEG for $t\bar{t}$ background. The simulated leptonic background samples were normalised to the integrated luminosity of the data using the predicted NNLO or NLO + NNLL cross sections. The number of QCD background events was estimated by fitting, in each jet multiplicity bin, the E_T^{miss} distribution in the data (without

the E_T^{miss} and M_T cuts) to a sum of two templates: one for the QCD background and another which included signal and the leptonic backgrounds. In both muon and electron channels, the shapes for the second template were obtained from simulation. In the electron channel, the template for the QCD background was obtained from the data because the mechanisms by which a jet fakes an electron are difficult to simulate. This template was derived from a data sample where looser electron identification criteria were applied on the shower shapes and the track-cluster matching requirements were inverted. In the muon channel, the QCD template was obtained from simulations. The QCD background was computed from the results of the template fit. In the electron channel, the fit was performed in the region $E_T^{\text{miss}} > 10$ GeV due to the poor understanding of the background below 10 GeV. The fit to the E_T^{miss} distribution was used only to determine the QCD background normalisation, taking into account contributions from leptonic background and signal in the low E_T^{miss} region. The W + jet signal yield for the cross section calculation was derived as the difference between the observed number of events in the signal region and the sum of background components. Fig. 1 shows the E_T^{miss} distribution for events with one jet, with the fitted contributions from all background sources in the electron and muon channels respectively, after all the other selection requirements (except for the M_T and E_T^{miss} requirements) have been applied. The residual difference in E_T^{miss} between the data and the QCD template in the control region is covered by the systematic uncertainties. The number of observed events and the estimated number of background events are summarised in Table 2.

The yield of signal events was corrected back to the particle level, taking into account detector and reconstruction efficiency. The dominant corrections in the electron channel come from electron reconstruction efficiency ($\approx 20\%$ correction). In the muon channel, the dominant corrections come from trigger and reconstruction efficiency (corrections of $\approx 10\text{--}20\%$ and $\approx 10\%$ respectively). The corrections were computed using the ALPGEN W + jets event generator plus full detector simulation, restricting the events to the same phase space as the data analysis. The phase space requirements were applied to generated quantities. In this analysis, particle-level jets were constructed in simulated events by applying the jet finder to all final state particles (excluding muons and neutrinos) with a lifetime longer than 10 ps, whether produced directly in the pp collision or from the decay of particles with shorter lifetimes. Correction factors were computed as one-dimensional functions of jet multiplicity and p_T of the leading and next-to-leading jets, and were treated as independent. Migration of events across bins of jet p_T was made small compared to the

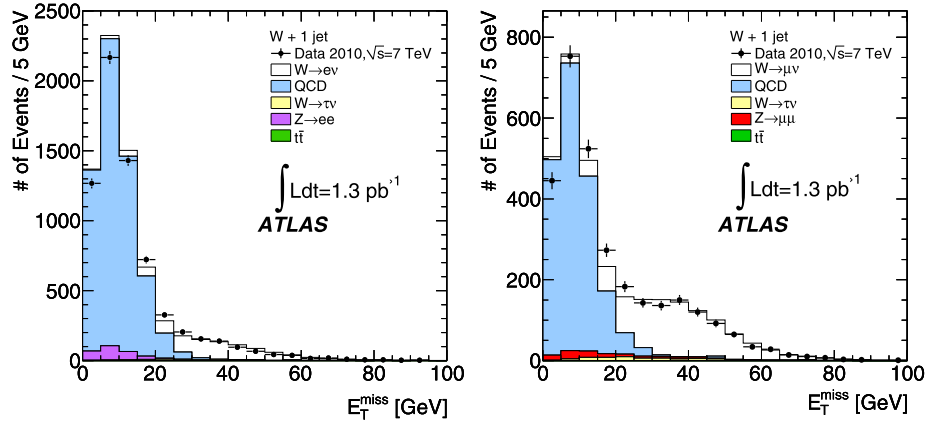


Fig. 1. Results of fitting the signal and background templates to the E_T^{miss} distribution in the electron (left) and muon (right) channels for the 1-jet bin. In the electron channel, the fit was performed for $E_T^{\text{miss}} > 10$ GeV. All templates were from simulated events, except for the QCD background template in the electron channel which was obtained from the data.

Table 2
Summary of background yields and observed number of events for the electron and muon channels with systematic uncertainties, excluding the luminosity uncertainty. Statistical uncertainties are negligible compared to systematic uncertainties. The uncertainty in the backgrounds due to the luminosity uncertainty is 11% for all backgrounds except for the QCD background, since it was normalised to the data. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio.

Electron channel process	$N_{\text{jet}} \geq 0$	$N_{\text{jet}} \geq 1$	$N_{\text{jet}} \geq 2$	$N_{\text{jet}} \geq 3$	$N_{\text{jet}} \geq 4$
QCD	130^{+20}_{-60}	100^{+20}_{-40}	45^{+7}_{-20}	18^{+3}_{-8}	–
$W \rightarrow \tau \nu$	113 ± 11	25 ± 5	4 ± 2	0.5 ± 0.4	–
$Z \rightarrow ee$	10 ± 8	7 ± 6	3 ± 2	1 ± 1	–
$t\bar{t}$	17 ± 2	17 ± 2	17 ± 2	14 ± 2	–
Observed in data	4216	987	276	83	–
Muon channel process	$N_{\text{jet}} \geq 0$	$N_{\text{jet}} \geq 1$	$N_{\text{jet}} \geq 2$	$N_{\text{jet}} \geq 3$	$N_{\text{jet}} \geq 4$
QCD	30 ± 20	20 ± 13	4^{+10}_{-4}	2 ± 2	1 ± 1
$W \rightarrow \tau \nu$	133 ± 12	24 ± 6	5 ± 2	0.9 ± 0.5	0.4 ± 0.3
$Z \rightarrow \mu\mu$	170 ± 14	30 ± 4	8 ± 1	2 ± 0.5	0.6 ± 0.2
$t\bar{t}$	18 ± 2	18 ± 2	18 ± 2	16 ± 2	11 ± 1
Observed in data	4911	1049	292	95	36

statistical uncertainty by selecting the bin widths to be at least a factor of two larger than the jet p_T resolution [31]. Tests with simulated data showed that these correction factors were sufficient to recover particle-level distributions. To treat the effect of final state QED radiation, the energy of the generated lepton was defined as the energy of the lepton after radiation plus the energy of all radiated photons within $\Delta R = 0.1$ around the lepton.

The correction factor for the trigger efficiency was obtained directly from the data as follows. In the electron channel, events were triggered either by an independent E_T^{miss} trigger or a loose electron trigger with an approximately 5 GeV threshold. The full $W + \text{jets}$ selection was carried out in essentially the same way as described above in order to isolate a pure electron sample. The main difference was in the QCD background estimation, which was done with templates for the shape of the electron isolation distribution, where the isolation variable was defined as the sum of transverse energy in a cone of $\Delta R = 0.4$ around the electron divided by the transverse energy of the electron. These templates were obtained by inverting one or more of the electron shower shape requirements. The electron trigger efficiency was found to be close to 100% in both data and simulation. In the muon channel, the trigger efficiency was computed with a sample of unbiased offline reconstructed muons from $Z \rightarrow \mu\mu$ decays. Average trigger efficiencies of $82.0 \pm 1.4\%$ and $86.9 \pm 0.1\%$ were obtained in data and simulation, respectively; the difference between data and simulation comes from a mismodelling of both the efficiency of

the forward muon chambers and of the programming of the muon trigger electronics. The trigger efficiency (and its uncertainty) from the data was used for the correction factor.

6. Systematic uncertainties

The primary sources of systematic uncertainty in the cross section for both electron and muon channels are uncertainties in the integrated luminosity and in the jet energy scale [31]. In the electron channel, the uncertainty due to the QCD background shape is also important. Both electron and muon channels are affected by uncertainties in the lepton reconstruction efficiency. The luminosity uncertainty enters primarily through the signal normalisation but also has an effect on the estimation of the leptonic backgrounds; the luminosity uncertainty is therefore larger in the muon channel.

Uncertainties in the jet energy scale (JES) and jet energy resolution (JER) were determined primarily from simulations [31]. The JES uncertainty varies as a function of jet p_T and η , and ranges from around 10% at 20 GeV to about 8% at 100 GeV. The JER uncertainty is 14% of the jet energy resolution. To take into account the differences in calorimeter response to quark- and gluon-initiated jets, an additional uncertainty of 5% was added in quadrature to the JES uncertainty, based on the average difference in simulation of the calorimeter response between jets in the $W + \text{jets}$ samples compared to those in the dijet samples (on which the JES

calibration is based). Uncertainties in the JES due to nearby jets in $W + \text{jets}$ events were also studied but found to be small. To estimate the impact of the JES uncertainty, jet energies in the simulated events were shifted by the JES uncertainty, and the E_T^{miss} vector was recomputed. In addition, calorimeter clusters not associated to a jet or electron, such as those coming from the underlying event, were scaled using a p_T -dependent uncertainty [27], ranging from $\pm 20\%$ for $p_T \simeq 500$ MeV to $\pm 5\%$ at high p_T . Similarly the jet energies were smeared with a Gaussian representing the JER uncertainty and the E_T^{miss} vector was recomputed. The full analysis was repeated with these variations, and the cross sections were recomputed; the change in the cross section was taken as the systematic uncertainty. The impact of the JES and E_T^{miss} uncertainties on the cross section uncertainty was approximately 10%.

A significant source of uncertainty in the electron channel is the potential bias in the sample selection for building the template shape of the QCD background; with the current selection requirements, the contribution from semileptonic heavy flavour decays is underestimated. The size of the effect was determined with simulated events by comparing the background estimates from two templates: one based on the electron selection used for this cross section measurement and the other based on the selection used for the QCD background estimation in the electron channel. The resulting uncertainty on the QCD background estimate, including significant contributions from the limited statistics of the simulated event samples, was as high as 50%, but the effect on the cross section for the inclusive 1-jet bin was about 5%. The fit region for the QCD background was varied by ± 5 GeV to account for shape differences in the low E_T^{miss} region; the resulting uncertainty on the cross section was 1–2%.

The uncertainty in the electron identification efficiency was taken from the inclusive cross section measurement [27]. By examining the reconstruction efficiency in simulated events as a function of the ΔR separation between the jet and the electron, the reconstruction efficiency was found to be consistent with the value in Ref. [27]. Furthermore, in the region $\Delta R > 0.5$, the efficiency was found to be constant as a function of ΔR and as a function of jet multiplicity. The uncertainty in the muon reconstruction efficiency was estimated by comparing the efficiency measured with simulated events to that measured in the data with muons from $Z \rightarrow \mu\mu$ decays, following a method similar to that described in Ref. [27]. The resulting uncertainties in the cross section were approximately 5.5% in both electron and muon channels.

Other uncertainties which were considered include the trigger efficiency, jet reconstruction efficiency, lepton momentum scale and resolution, pile-up, and biases in the procedure for correcting for detector effects (for example, by comparing correction factors obtained with ALPGEN to those obtained with SHERPA). Their effect on the cross section was found to be smaller than the uncertainties described above. For example, the uncertainty on the electron energy resolution was based on extrapolations from test-beam measurements [27] and had a $< 0.1\%$ effect on the cross section. All of the above systematic uncertainties (except for the bias in the template shape for the QCD background in the electron channel) were also applied to the estimates of the QCD and leptonic backgrounds in both electron and muon channels. In addition, for the leptonic backgrounds the uncertainty in the NNLO cross sections was taken to be 5% for W/Z production as in Ref. [27]. The $t\bar{t}$ cross section uncertainty was taken to be approximately 7%, amounting to the sum in quadrature of PDF uncertainties (3%) and uncertainties estimated by varying renormalisation and factorisation scales (6%) [33,34]. The resulting uncertainty on the $W + \text{jets}$ cross section ranged from 0.1 to 2%, depending on the jet multiplicity, and was small compared to other systematic uncertainties.

The systematic uncertainties in the cross section measurement are summarised in Table 3 for $N_{\text{jet}} \geq 1$; most of the uncertainties are approximately independent of jet multiplicity, except for the uncertainty due to the jet energy scale and resolution, and the QCD background in the electron channel. The dominant systematic uncertainties are shown as a function of jet multiplicity and leading jet p_T in Fig. 2. Both distributions are similar for electron and muon channels; the uncertainty is therefore shown as a function of jet multiplicity for the electron channel and as a function of leading jet p_T for the muon channel. The main contribution to the other uncertainties in the electron channel comes from the QCD background (especially at high jet multiplicities), the electron identification efficiency and the electron energy scale. For the muon channel, the main contribution is from the muon reconstruction efficiency.

In the cross section ratio measurement, the uncertainty due to the jet energy scale uncertainty remains the dominant effect, amounting to approximately 10% on the ratio. The luminosity uncertainty does not completely cancel in the ratio because the background estimates are affected by the luminosity uncertainty and the background levels vary as a function of jet multiplicity.

7. Results and conclusions

The measured $W + \text{jets}$ cross section (multiplied by the leptonic branching ratio) and the cross section ratios are shown as a function of corrected jet multiplicity in Tables 4 and 5 respectively, as well as in Figs. 3 and 4. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. The cross sections are quoted in the limited kinematic region: $E_T^j > 20$ GeV, $|\eta^j| < 2.8$, $E_T^\ell > 20$ GeV, $|\eta^\ell| < 2.47$ (excluding $1.37 < |\eta^\ell| < 1.52$), $|\eta^\mu| < 2.4$, $p_T^\nu > 25$ GeV, $M_T > 40$ GeV, $\Delta R^{lj} > 0.5$, where ℓ , j and ν denote lepton, jet and neutrino, respectively. The quantities p_T^ℓ , $|\eta^\ell|$, and M_T include the energy of all radiated photons within $\Delta R = 0.1$ around the lepton. The $W + \text{jets}$ cross section (times leptonic branching ratio) is shown as a function of the p_T of the leading and next-to-leading jets in the event in Fig. 5; the leading jet is shown for $N_{\text{jet}} \geq 1$ and the next-to-leading jet is shown for $N_{\text{jet}} \geq 2$.

Also shown in Figs. 3, 4, and 5 are particle-level expectations from PYTHIA, ALPGEN and SHERPA simulations as well as a calculation using MCFM v5.8 [35]. PYTHIA is LO, while ALPGEN and SHERPA match higher-multiplicity matrix elements to a leading-logarithmic parton shower; these predictions have been normalised to the NNLO inclusive W production cross section. The version of MCFM used here provides NLO predictions at parton level for W -boson production with $N_{\text{jet}} \leq 2$; only leading-order predictions are available for $W + \text{three jets}$. No additional normalisation was applied to the MCFM predictions.

The MCFM results were obtained with the same jet algorithm and same kinematic selection requirements as applied to the data. Renormalisation and factorisation scales were set to $H_T/2$, where H_T is the scalar sum of the p_T of the unclustered partons and of the lepton and neutrino from the W decay. The PDFs were CTEQ6L1 [11] and CTEQ6.6M [15] for the LO and NLO calculations, respectively. Corrections for hadronisation and underlying event were computed with PYTHIA as a function of leading and next-to-leading jet p_T . Hadronisation and underlying event corrections ranged from -10% to -4% and $+10\%$ to $+4\%$, respectively, for jet $p_T \simeq 20$ GeV to jet $p_T > 80$ GeV. The partial cancellation of hadronisation and underlying event corrections [5] results in an overall correction of approximately 4%. The effect of final state QED radi-

Table 3

Summary of the systematic uncertainties in the cross section. The uncertainties are shown only for $N_{\text{jet}} \geq 1$. The sign convention for the JES and lepton energy scale uncertainties is such that a positive change in the energy scale results in an increase in the jet or lepton energy observed in the data.

<i>e</i> channel		
Effect	Range	Cross section uncertainty (%)
Jet energy scale and E_T^{miss}	$\pm 10\%$ (dependent on jet η and p_T) $\oplus 5\%$	+11, −9
Jet energy resolution	14% on each jet	± 1.0
Electron trigger	$\pm 0.5\%$	∓ 0.7
Electron identification	$\pm 5.2\%$	∓ 5.5
Electron energy scale	$\pm 3\%$	+3.9, −4.7
Pile-up removal cut	4–7% in lowest jet p_T bin	± 1.9
Residual pile-up effects	from simulation	± 2.2
QCD background shape	from template variation	−1.5, +5.2
Luminosity	$\pm 11\%$	−10, +13

μ channel		
Effect	Range	Cross section uncertainty (%)
Jet energy scale and E_T^{miss}	$\pm 10\%$ (dependent on jet η and p_T) $\oplus 5\%$	+11, −9
Jet energy resolution	14% on each jet	± 1.8
Muon trigger	$\pm 2.5\%$ in barrel, $\pm 2.0\%$ in endcap	∓ 1.6
Muon reconstruction	$\pm 5.6\%$	−5.4, +5.9
Muon momentum scale	$\pm 1\%$	+2, −0.9
Muon momentum resolution	$\pm 5\%$ in barrel, $\pm 9\%$ in endcap	± 1.4
Pile-up removal cut	4–7% in lowest jet p_T bin	± 1.7
Residual pile-up effects	from simulation	± 1.4
Luminosity	$\pm 11\%$	−11, +13

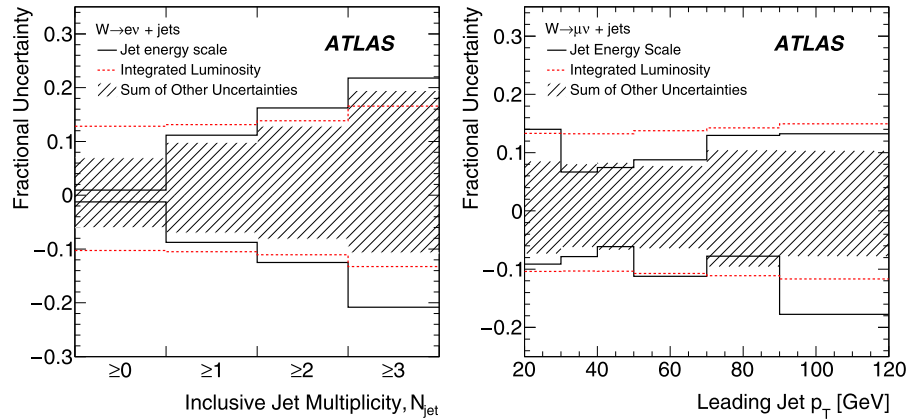


Fig. 2. Summary of the systematic uncertainties on the cross section measurement shown as a function of jet multiplicity in the electron channel (left) and leading-jet p_T in the muon channel (right). The jet energy scale uncertainty includes the uncertainty on E_T^{miss} . The main contribution to the “sum of other uncertainties” in the electron channel comes from the QCD background (especially at high jet multiplicities), the electron identification efficiency and the electron energy scale. For the muon channel, the main contribution is from the muon reconstruction efficiency.

Table 4

The measured cross section times leptonic branching ratio for $W + \text{jets}$ in the electron and muon channels as a function of corrected jet multiplicity with (in order) statistical, systematic, and luminosity uncertainties. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. Theoretical predictions from MCFM are also shown, with all uncertainties combined. MCFM provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

Jet multiplicity	$W \rightarrow e\nu$ (nb)	MCFM $W \rightarrow e\nu$ (nb)	$W \rightarrow \mu\nu$ (nb)	MCFM $W \rightarrow \mu\nu$ (nb)
≥ 0	$4.53 \pm 0.07^{+0.35+0.58}_{-0.30-0.47}$	$5.08^{+0.11}_{-0.30}$	$4.58 \pm 0.07^{+0.38+0.61}_{-0.32-0.48}$	$5.27^{+0.11}_{-0.32}$
≥ 1	$0.84 \pm 0.03^{+0.13+0.11}_{-0.10-0.09}$	$0.81^{+0.02}_{-0.04}$	$0.84 \pm 0.03^{+0.11+0.11}_{-0.09-0.09}$	$0.84^{+0.02}_{-0.04}$
≥ 2	$0.21 \pm 0.01^{+0.04+0.03}_{-0.03-0.02}$	$0.21^{+0.01}_{-0.02}$	$0.23 \pm 0.02^{+0.04+0.03}_{-0.03-0.02}$	$0.21^{+0.01}_{-0.02}$
≥ 3	$0.047 \pm 0.007^{+0.014+0.008}_{-0.011-0.006}$	0.05 ± 0.02	$0.064 \pm 0.008^{+0.016+0.010}_{-0.014-0.008}$	0.05 ± 0.02
≥ 4	–	–	$0.019 \pm 0.005 \pm 0.006^{+0.004}_{-0.003}$	–

ation from the electron or muon was computed with PYTHIA and ALPGEN (both using PHOTOS) and with SHERPA, comparing the acceptance before radiation with the acceptance after radiation, but summing up the photons within $\Delta R = 0.1$ around the lepton. This factor ($\simeq 1$ –2%) was applied as a correction to the MCFM prediction.

The systematic uncertainty in the MCFM cross sections due to fragmentation was estimated by comparing PYTHIA with HERWIG. Underlying event uncertainties were estimated by comparing the AMBT1 [19] event generator tune with the tune from JIMMY [10] as well as by varying the AMBT1 tune to increase the underlying event activity by approximately 10%. Renormalisation and factori-

Table 5

The measured cross section ratio for $W + \text{jets}$ in the electron and muon channels as a function of corrected jet multiplicity with (in order) statistical and systematic uncertainties. The cross section ratios are quoted in a limited and well-defined kinematic region, described in the text. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. Theoretical predictions from MCFM are also shown, with all uncertainties combined. MCFM provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

Jet multiplicity	$W \rightarrow e\nu$	MCFM $W \rightarrow e\nu$	$W \rightarrow \mu\nu$	MCFM $W \rightarrow \mu\nu$
$\geq 1/\geq 0$	$0.185 \pm 0.007^{+0.025}_{-0.019}$	$0.159^{+0.006}_{-0.005}$	$0.183 \pm 0.007^{+0.023}_{-0.020}$	$0.160^{+0.006}_{-0.005}$
$\geq 2/\geq 1$	$0.250 \pm 0.019^{+0.019}_{-0.010}$	$0.255^{+0.017}_{-0.022}$	$0.274 \pm 0.020^{+0.018}_{-0.011}$	$0.255^{+0.017}_{-0.021}$
$\geq 3/\geq 2$	$0.224 \pm 0.037 \pm 0.022$	$0.241^{+0.108}_{-0.061}$	$0.278 \pm 0.041^{+0.024}_{-0.020}$	$0.242^{+0.104}_{-0.061}$
$\geq 4/\geq 3$	–	–	$0.297 \pm 0.088^{+0.037}_{-0.026}$	–

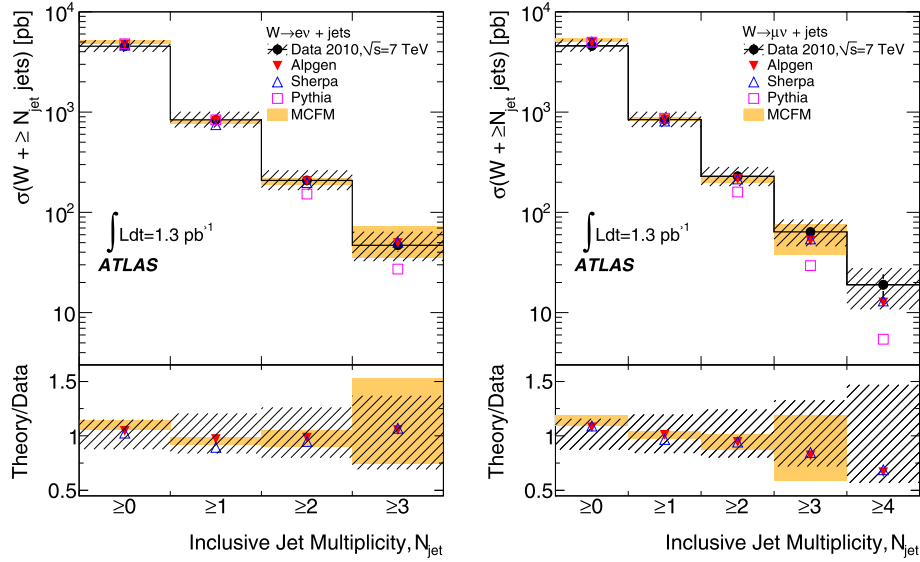


Fig. 3. $W + \text{jets}$ cross section results as a function of corrected jet multiplicity. Left: electron channel. Right: muon channel. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. For the data, the statistical uncertainties are shown by the vertical bars, and the combined statistical and systematic uncertainties are shown by the hashed regions. Note that the uncertainties are correlated from bin to bin. Also shown are predictions from PYTHIA, ALPGEN, SHERPA and MCFM, and the ratio of theoretical predictions to data (PYTHIA is not shown in the ratio). The theoretical uncertainties are shown only for MCFM, which provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

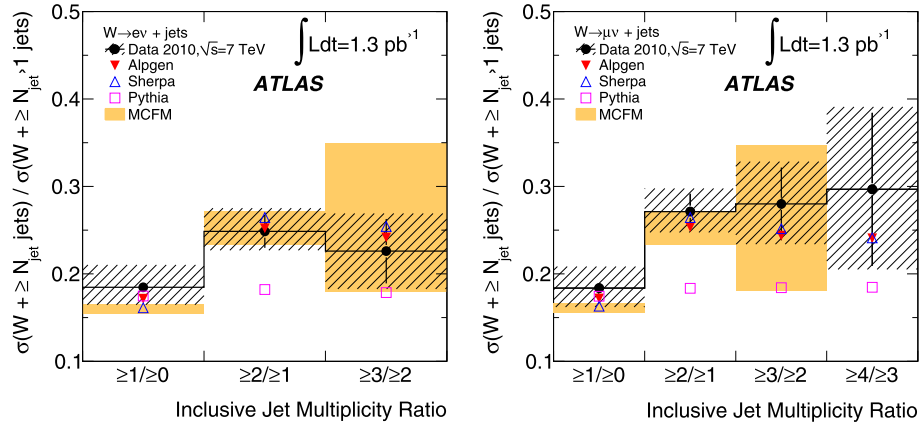


Fig. 4. $W + \text{jets}$ cross section ratio results as a function of corrected jet multiplicity. Left: electron channel. Right: muon channel. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. For the data, the statistical uncertainties are shown by the vertical bars, and the combined statistical and systematic uncertainties are shown by the hashed regions. Also shown are theoretical predictions from PYTHIA, ALPGEN, SHERPA, and MCFM. The theoretical uncertainties are shown only for MCFM, which provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

sation scale uncertainties were estimated by varying the scales, in all combinations, up and down, by factors of two. PDF uncertainties were computed by summing in quadrature the dependence on each of the 22 eigenvectors characterising the CTEQ6.6 PDF set; the uncertainty in α_s was also taken into account. An alternative PDF set, MSTW2008 [13], with its set of 68% C.L. eigenvectors was

also examined, and the envelope of the uncertainties from CTEQ6.6 and MSTW2008 was taken as the final PDF uncertainty. The total resulting uncertainties are given in Tables 4 and 5.

In conclusion, this Letter presents a measurement of the $W + \text{jets}$ cross section as a function of jet multiplicity in pp collisions at $\sqrt{s} = 7$ TeV in both electron and muon decay modes of the

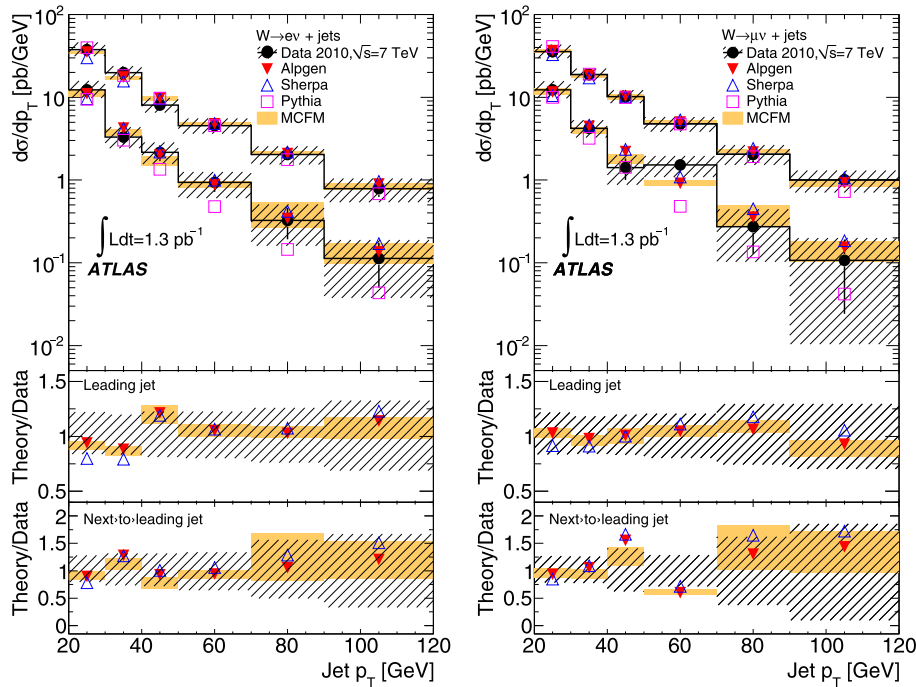


Fig. 5. W + jets cross section as a function of the p_T of the two leading jets in the event. The p_T of the leading jet is shown for events with ≥ 1 jet while the p_T of the next-to-leading jet is shown for events with ≥ 2 jets. Left: electron channel. Right: muon channel. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. For the data, the statistical uncertainties are shown by the vertical bars, and the combined statistical and systematic uncertainties are shown by the hashed regions. Also shown are theoretical predictions from PYTHIA, ALPGEN, SHERPA and MCFM, and the ratio of theoretical predictions to data (PYTHIA is not shown in the ratio). The theoretical uncertainties are shown only for MCFM, which provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

W -boson, based on an integrated luminosity of 1.3 pb^{-1} recorded with the ATLAS detector. Measurements are also presented of the ratio of cross sections $\sigma(W + \geq n)/\sigma(W + \geq n - 1)$ for inclusive jet multiplicities $n = 1-4$, and of the p_T distribution of the leading and next-to-leading jets in the event. The results have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics. This range is fully covered by the detector acceptance, so as to avoid model-dependent extrapolations and to facilitate comparisons with theoretical predictions. As expected, the PYTHIA samples considered, which contain a $2 \rightarrow 1$ matrix element merged with a $2 \rightarrow 2$ matrix element and a leading-logarithmic parton shower, does not provide a good description of the data for jet multiplicities greater than one. Good agreement is observed with the predictions of the multi-parton matrix element generators ALPGEN and SHERPA. Calculations based on $O(\alpha_s^2)$ matrix elements in MCFM (available for jet multiplicities $n \leq 2$) are also in good agreement with the data.

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ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, A.A. Abdelalim⁴⁹, A. Abdesselam¹¹⁸, O. Abdinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, H. Abramowicz¹⁵³, H. Abreu¹¹⁵, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, M. Ackers²⁰, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁵, M. Aderholz⁹⁹, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, M.S. Alam¹, M.A. Alam⁷⁶, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁵, M. Aleppo^{89a,89b}, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob²⁰, M. Aliev¹⁵, G. Alimonti^{89a}, J. Alison¹²⁰, M. Aliyev¹⁰, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷¹, A. Alonso⁷⁹, J. Alonso¹⁴, M.G. Alviggi^{102a,102b}, K. Amako⁶⁶, P. Amaral²⁹, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,b}, G. Amorós¹⁶⁷, N. Amram¹⁵³, C. Anastopoulos¹³⁹, T. Andeen³⁴, C.F. Anders²⁰, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M.-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, S. Antonelli^{19a,19b}, J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³, L. Aperio Bella⁴, R. Apolle¹¹⁸, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁶, A.T.H. Arce⁴⁴, J.P. Archambault²⁸, S. Arfaoui^{29,c}, J.-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, K.E. Arms¹⁰⁹, S.R. Armstrong²⁴, O. Arnaez⁸¹, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷², S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵, K. Assamagan²⁴, A. Astbury¹⁶⁹, A. Astvatsatourov⁵², G. Atoian¹⁷⁵, B. Aubert⁴, B. Auerbach¹⁷⁵, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aurousseau⁴, N. Austin⁷³, R. Avramidou⁹, D. Axen¹⁶⁸, C. Ay⁵⁴, G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, G. Bachy²⁹, M. Backes⁴⁹, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁵, S. Baker⁷⁷, F. Baltasar Dos Santos Pedrosa²⁹, E. Banas³⁸, P. Banerjee⁹³, Sw. Banerjee¹⁶⁹, D. Banfi^{89a,89b}, A. Bangert¹³⁷, V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷¹, S.P. Baranov⁹⁴, A. Barashkou⁶⁵, A. Barbaro Galtieri¹⁴, T. Barber²⁷, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁵, T. Barillari⁹⁹, M. Barisonzi¹⁷⁴, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, A.E. Barton⁷¹, D. Bartsch²⁰, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, G. Battistoni^{89a}, F. Bauer¹³⁶, H.S. Bawa¹⁴³, B. Beare¹⁵⁸, T. Beau⁷⁸, P.H. Beauchemin¹¹⁸, R. Beccherle^{50a}, P. Bechtel⁴¹, H.P. Beck¹⁶, M. Beckingham⁴⁸, K.H. Becks¹⁷⁴, A.J. Beddall^{18c}, A. Beddall^{18c}, V.A. Bednyakov⁶⁵, C. Bee⁸³, M. Begel²⁴, S. Behar Harpaz¹⁵², P.K. Behera⁶³, M. Beimforde⁹⁹, C. Belanger-Champagne¹⁶⁶, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹, G. Bellomo^{89a,89b}, M. Bellomo^{119a}, A. Belloni⁵⁷, K. Belotskiy⁹⁶, O. Beltramello²⁹, S. Ben Ami¹⁵², O. Benary¹⁵³, D. Benchekroun^{135a}, C. Benchouk⁸³, M. Bendel⁸¹, B.H. Benedict¹⁶³,

N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²², K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹, E. Berglund⁴⁹, J. Beringer¹⁴, K. Bernadet⁸³, P. Bernat¹¹⁵, R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶, A. Bertin^{19a,19b}, F. Bertinelli²⁹, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{72a,72b}, O. Biebel⁹⁸, J. Biesiada¹⁴, M. Biglietti^{132a,132b}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁷, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵, J.-B. Blanchard¹¹⁵, G. Blanchot²⁹, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷, A. Bocci⁴⁴, R. Bock²⁹, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁴, N. Boelaert³⁵, S. Böser⁷⁷, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Böhm^{146a}, V. Boisvert⁷⁶, T. Bold^{163,e}, V. Boldea^{25a}, M. Bona⁷⁵, M. Boonekamp¹³⁶, G. Boorman⁷⁶, C.N. Booth¹³⁹, P. Booth¹³⁹, J.R.A. Booth¹⁷, S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{12a}, S. Borroni^{132a,132b}, K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, C. Boulahouache¹²³, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁵, N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, A. Braem²⁹, E. Brambilla^{72a,72b}, P. Branchini^{134a}, G.W. Brandenburg⁵⁷, A. Brandt⁷, G. Brandt⁴¹, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun¹⁷⁴, B. Brelmer¹⁵⁸, J. Bremer²⁹, R. Brenner¹⁶⁶, S. Bressler¹⁵², D. Breton¹¹⁵, N.D. Brett¹¹⁸, P.G. Bright-Thomas¹⁷, D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, T.J. Brodbeck⁷¹, E. Brodet¹⁵³, F. Broggi^{89a}, C. Bromberg⁸⁸, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², E. Brubaker³⁰, P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶¹, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³, F. Bucci⁴⁹, J. Buchanan¹¹⁸, N.J. Buchanan², P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁵, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, D. Buira-Clark¹¹⁸, E.J. Buis¹⁰⁵, O. Bulekov⁹⁶, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³, T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶, F. Butin²⁹, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁷, T. Byatt⁷⁷, S. Cabrera Urbán¹⁶⁷, M. Caccia^{89a,89b}, D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, S. Calvet³³, A. Camard⁷⁸, P. Camarri^{133a,133b}, M. Cambiaghi^{119a,119b}, D. Cameron¹¹⁷, J. Cammin²⁰, S. Campana²⁹, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³⁰, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo¹⁴⁸, C. Caramarcu^{25a}, R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron^{159a}, S. Caron⁴⁸, C. Carpentieri⁴⁸, G.D. Carrillo Montoya¹⁷², S. Carron Montero¹⁵⁸, A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,f}, D. Casadei¹⁰⁸, M.P. Casado¹¹, M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷², E. Castaneda-Miranda¹⁷², V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124b,a}, G. Cataldi^{72a}, F. Cataneo²⁹, A. Catinaccio²⁹, J.R. Catmore⁷¹, A. Cattai²⁹, G. Cattani^{133a,133b}, S. Caughron⁸⁸, A. Cavallari^{132a,132b}, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b}, A. Cazzato^{72a,72b}, F. Ceradini^{134a,134b}, C. Cerna⁸³, A.S. Cerqueira^{23a}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷, S.A. Cetin^{18b}, F. Cevenini^{102a,102b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, K. Chan², B. Chapleau⁸⁵, J.D. Chapman²⁷, J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸², S. Cheatham⁷¹, S. Chekanov⁵, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁵, H. Chen²⁴, L. Chen², S. Chen^{32c}, T. Chen^{32c}, X. Chen¹⁷², S. Cheng^{32a}, A. Cheplakov⁶⁵, V.F. Chepurinov⁶⁵, R. Cherkaoui El Moursli^{135d}, V. Chernyatin²⁴, E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, F. Chevallier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani⁵¹, J.T. Childers^{58a}, A. Chilingarov⁷¹, G. Chiodini^{72a}, M.V. Chizhov⁶⁵, G. Choudalakis³⁰, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, M.D. Ciobotaru¹⁶³, C. Ciocca^{19a,19b}, A. Ciochio¹⁴, M. Cirilli⁸⁷, M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, R.W. Clift¹²⁹, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro^{50a,50b}, J. Cochran⁶⁴, P. Coe¹¹⁸, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁷, C.D. Cojocar²⁸, J. Colas⁴, A.P. Colijn¹⁰⁵, C. Collard¹¹⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵, G. Colon⁸⁴, R. Coluccia^{72a,72b}, G. Comune⁸⁸, P. Conde Muiño^{124a}, E. Coniavitis¹¹⁸, M.C. Conidi¹¹, M. Consonni¹⁰⁴, S. Constantinescu^{25a}, C. Conta^{119a,119b}, F. Conventi^{102a,g}, J. Cook²⁹, M. Cooke¹⁴, B.D. Cooper⁷⁵, A.M. Cooper-Sarkar¹¹⁸, N.J. Cooper-Smith⁷⁶, K. Copic³⁴, T. Cornelissen^{50a,50b}, M. Corradi^{19a}, S. Correard⁸³, F. Corriveau^{85,h}, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a},

M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹, R. Coura Torres^{23a}, L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸, M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b}, S. Crépe-Renaudin⁵⁵, C. Cuenca Almenar¹⁷⁵, T. Cuhadar Donszelmann¹³⁹, S. Cuneo^{50a,50b}, M. Curatolo⁴⁷, C.J. Curtis¹⁷, P. Cwetanski⁶¹, H. Czirr¹⁴¹, Z. Czyczula¹¹⁷, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{132a,132b}, A. Da Rocha Gesualdi Mello^{23a}, P.V.M. Da Silva^{23a}, C. Da Via⁸², W. Dabrowski³⁷, A. Dahlhoff⁴⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴, S.J. Dallison^{129,*}, M. Dam³⁵, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson²⁹, R. Dankers¹⁰⁵, D. Dannheim⁹⁹, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b}, C. Daum¹⁰⁵, J.P. Dauvergne²⁹, W. Davey⁸⁶, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, M. Davies⁹³, A.R. Davison⁷⁷, E. Dawe¹⁴², I. Dawson¹³⁹, J.W. Dawson^{5,*}, R.K. Daya³⁹, K. De⁷, R. de Asmundis^{102a}, S. De Castro^{19a,19b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, E. De La Cruz-Burelo⁸⁷, C. De La Taille¹¹⁵, B. De Lotto^{164a,164c}, L. De Mora⁷¹, L. De Nooij¹⁰⁵, M. De Oliveira Branco²⁹, D. De Pedis^{132a}, P. de Saintignon⁵⁵, A. De Salvo^{132a}, U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, S. Dean⁷⁷, G. Dedes⁹⁹, D.V. Dedovich⁶⁵, J. Degenhardt¹²⁰, M. Dehchar¹¹⁸, M. Deile⁹⁸, C. Del Papa^{164a,164c}, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, A. Dell'Acqua²⁹, L. Dell'Asta^{89a,89b}, M. Della Pietra^{102a,g}, D. della Volpe^{102a,102b}, M. Delmastro²⁹, P. Delpierre⁸³, N. Delruelle²⁹, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸, S. Demers¹⁷⁵, M. Demichev⁶⁵, B. Demirköz¹¹, J. Deng¹⁶³, S.P. Denisov¹²⁸, C. Dennis¹¹⁸, D. Derendarz³⁸, J.E. Derkaoui^{135c}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁵⁸, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,i}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹, B. Di Girolamo²⁹, S. Di Luise^{134a,134b}, A. Di Mattia⁸⁸, R. Di Nardo^{133a,133b}, A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c}, E.B. Diehl⁸⁷, H. Dietl⁹⁹, J. Dietrich⁴⁸, T.A. Dietzsch^{58a}, S. Diglio¹¹⁵, K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a}, F. Dittus²⁹, F. Djama⁸³, R. Djilkibaev¹⁰⁸, T. Djobava⁵¹, M.A.B. do Vale^{23a}, A. Do Valle Wemans^{124a}, T.K.O. Doan⁴, M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos⁴², E. Dobson²⁹, M. Dobson¹⁶³, J. Dodd³⁴, O.B. Dogan^{18a,*}, C. Doglioni¹¹⁸, T. Doherty⁵³, Y. Doi^{66,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshein⁹⁶, T. Dohmae¹⁵⁵, M. Donadelli^{23b}, M. Donega¹²⁰, J. Donini⁵⁵, J. Dopke¹⁷⁴, A. Doria^{102a}, A. Dos Anjos¹⁷², M. Dosil¹¹, A. Dotti^{122a,122b}, M.T. Dova⁷⁰, J.D. Dowell¹⁷, A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, Z. Drasal¹²⁶, J. Drees¹⁷⁴, N. Dressnandt¹²⁰, H. Drevermann²⁹, C. Driouichi³⁵, M. Dris⁹, J.G. Drohan⁷⁷, J. Dubbert⁹⁹, T. Dubbs¹³⁷, S. Dube¹⁴, E. Duchovni¹⁷¹, G. Duckeck⁹⁸, A. Dudarev²⁹, F. Dudziak¹¹⁵, M. Dührssen²⁹, I.P. Duerdoth⁸², L. Duflot¹¹⁵, M.-A. Dufour⁸⁵, M. Dunford²⁹, H. Duran Yildiz^{3b}, R. Duxfield¹³⁹, M. Dwuznik³⁷, F. Dydak²⁹, D. Dzahini⁵⁵, M. Düren⁵², J. Ebke⁹⁸, S. Eckert⁴⁸, S. Eckweiler⁸¹, K. Edmonds⁸¹, C.A. Edwards⁷⁶, I. Efthymiopoulos⁴⁹, W. Ehrenfeld⁴¹, T. Ehrich⁹⁹, T. Eifert²⁹, G. Eigen¹³, K. Einsweiler¹⁴, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi⁴, M. Ellert¹⁶⁶, S. Elles⁴, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹, R. Ely¹⁴, D. Emelianov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶², A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, D. Eriksson^{146a}, J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, C. Escobar¹⁶⁷, X. Espinal Curull¹¹, B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etienve¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶¹, L. Fabbri^{19a,19b}, C. Fabre²⁹, K. Facius³⁵, R.M. Fakhruddinov¹²⁸, S. Falciano^{132a}, A.C. Falou¹¹⁵, Y. Fang¹⁷², M. Fanti^{89a,89b}, A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S.M. Farrington¹¹⁸, P. Farthouat²⁹, D. Fasching¹⁷², P. Fassnacht²⁹, D. Fassouliotis⁸, B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a}, O.L. Fedin¹²¹, I. Fedorko²⁹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, D. Fellmann⁵, C.U. Felzmann⁸⁶, C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, D. Ferguson¹⁷², J. Ferland⁹³, B. Fernandes^{124a,j}, W. Fernando¹⁰⁹, S. Ferrag⁵³, J. Ferrando¹¹⁸, V. Ferrara⁴¹, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, A. Ferrer¹⁶⁷, M.L. Ferrer⁴⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³⁰, F. Fiedler⁸¹, A. Filipčič⁷⁴, A. Filippas⁹, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,f}, L. Fiorini¹¹, A. Firan³⁹, G. Fischer⁴¹, P. Fischer²⁰, M.J. Fisher¹⁰⁹, S.M. Fisher¹²⁹, J. Flammer²⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷³, S. Fleischmann²⁰, T. Flick¹⁷⁴, L.R. Flores Castillo¹⁷², M.J. Flowerdew⁹⁹, F. Föhlisch^{58a}, M. Fokitis⁹, T. Fonseca Martin¹⁶, D.A. Forbush¹³⁸, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, J.M. Foster⁸², D. Fournier¹¹⁵, A. Foussat²⁹, A.J. Fowler⁴⁴, K. Fowler¹³⁷, H. Fox⁷¹, P. Francavilla^{122a,122b}, S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷¹, M. Franklin⁵⁷, S. Franz²⁹, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁷, R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶,

E. Fullana Torregrosa²⁹, J. Fuster¹⁶⁷, C. Gabaldon²⁹, O. Gabizon¹⁷¹, T. Gadfort²⁴, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea⁹⁸, E.J. Gallas¹¹⁸, M.V. Gallas²⁹, V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, E. Galyaev⁴⁰, K.K. Gan¹⁰⁹, Y.S. Gao^{143,k}, V.A. Gapienko¹²⁸, A. Gaponenko¹⁴, F. Garberson¹⁷⁵, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro⁴⁹, R.W. Gardner³⁰, N. Garelli²⁹, H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, O. Gaumer⁴⁹, B. Gaur¹⁴¹, L. Gauthier¹³⁶, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, J.-C. Gayde²⁹, E.N. Gazis⁹, P. Ge^{32d}, C.N.P. Gee¹²⁹, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁹⁸, S. Gentile^{132a,132b}, F. Georgatos⁹, S. George⁷⁶, P. Gerlach¹⁷⁴, A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135d}, P. Ghez⁴, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b}, V. Giakoumopoulou⁸, V. Giangiobbe^{122a,122b}, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson²⁹, G.F. Gieraltowski⁵, L.M. Gilbert¹¹⁸, M. Gilchriese¹⁴, O. Gildemeister²⁹, V. Gilevsky⁹¹, D. Gillberg²⁸, A.R. Gillman¹²⁹, D.M. Gingrich^{2,d}, J. Ginzburg¹⁵³, N. Giokaris⁸, R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁴, G.L. Glonti⁶⁵, J. Godfrey¹⁴², J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷, D. Goldin³⁹, T. Golling¹⁷⁵, N.P. Gollub²⁹, S.N. Golovnia¹²⁸, A. Gomes^{124a,l}, L.S. Gomez Fajardo⁴¹, R. Gonçalo⁷⁶, L. Gonella²⁰, C. Gong^{32b}, A. Gonidec²⁹, S. Gonzalez¹⁷², S. González de la Hoz¹⁶⁷, M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³, G. Gorfine¹⁷⁴, B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸, S.A. Gorokhov¹²⁸, B.T. Gorski²⁹, V.N. Goryachev¹²⁸, B. Gosdzik⁴¹, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁵, M. Gouanère⁴, I. Gough Eschrich¹⁶³, M. Gouighri^{135a}, D. Goujdami^{135a}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸, C. Goy⁴, I. Grabowska-Bold^{163,e}, V. Grabski¹⁷⁶, P. Grafström²⁹, C. Grah¹⁷⁴, K.-J. Grah¹⁴⁷, F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray^{34,m}, J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, D. Greenfield¹²⁹, T. Greenshaw⁷³, Z.D. Greenwood^{24,i}, I.M. Gregor⁴¹, P. Grenier¹⁴³, E. Griesmayer⁴⁶, J. Griffiths¹³⁸, N. Grigalashvili⁶⁵, A.A. Grillo¹³⁷, K. Grimm¹⁴⁸, S. Grinstein¹¹, P.L.Y. Gris³³, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, J. Grognuz²⁹, M. Groh⁹⁹, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁴, J. Groth-Jensen⁷⁹, M. Gruwe²⁹, K. Grybel¹⁴¹, V.J. Guarino⁵, C. Guicheney³³, A. Guida^{72a,72b}, T. Guillemain⁴, S. Guindon⁵⁴, H. Guler^{85,n}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁴, A. Gupta³⁰, Y. Gusakov⁶⁵, V.N. Gushchin¹²⁸, A. Gutierrez⁹³, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷², C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴, R. Hackenburg²⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner⁹⁹, F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁶, J. Haller⁵⁴, K. Hamacher¹⁷⁴, A. Hamilton⁴⁹, S. Hamilton¹⁶¹, H. Han^{32a}, L. Han^{32b}, K. Hanagaki¹¹⁶, M. Hance¹²⁰, C. Handel⁸¹, P. Hanke^{58a}, C.J. Hansen¹⁶⁶, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵, P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁴, D. Harper⁸⁷, R.D. Harrington²¹, O.M. Harris¹³⁸, K. Harrison¹⁷, J.C. Hart¹²⁹, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁶, A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, M. Hatch²⁹, D. Hauff⁹⁹, S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁸, M. Havranek¹²⁵, B.M. Hawes¹¹⁸, C.M. Hawkes¹⁷, R.J. Hawkins²⁹, D. Hawkins¹⁶³, T. Hayakawa⁶⁷, D. Hayden⁷⁶, H.S. Hayward⁷³, S.J. Haywood¹²⁹, E. Hazen²¹, M. He^{32d}, S.J. Head¹⁷, V. Hedberg⁷⁹, L. Heelan²⁸, S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵, L. Helary⁴, M. Heldmann⁴⁸, M. Heller¹¹⁵, S. Hellman^{146a,146b}, C. Helsens¹¹, R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴, A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³, C. Hensel⁵⁴, T. Henß¹⁷⁴, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, A.D. Hershenhorn¹⁵², G. Herten⁴⁸, R. Hertenberger⁹⁸, L. Hervas²⁹, N.P. Hessey¹⁰⁵, A. Hidvegi^{146a}, E. Higón-Rodriguez¹⁶⁷, D. Hill^{5,*}, J.C. Hill²⁷, N. Hill⁵, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴², D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹, M.R. Hoferkamp¹⁰³, J. Hoffman³⁹, D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, A. Holmes¹¹⁸, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, R.J. Homer¹⁷, Y. Homma⁶⁷, T. Horazdovsky¹²⁷, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸, J.-Y. Hostachy⁵⁵, T. Hott⁹⁹, S. Hou¹⁵¹, M.A. Houlden⁷³, A. Hoummada^{135a}, J. Howarth⁸², D.F. Howell¹¹⁸, I. Hristova⁴¹, J. Hrivnac¹¹⁵, I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu¹⁷⁵, S.-C. Hsu¹⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰, T.B. Huffman¹¹⁸, E.W. Hughes³⁴, G. Hughes⁷¹, R.E. Hughes-Jones⁸², M. Huhtinen²⁹, P. Hurst⁵⁷, M. Hurwitz¹⁴, U. Husemann⁴¹, N. Huseynov^{65,o}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci^{102a}, G. Iakovidis⁹, M. Ibbotson⁸²,

I. Ibragimov¹⁴¹, R. Ichimiya⁶⁷, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, M. Idzik³⁷, P. Iengo⁴, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁶, M. Ikeno⁶⁶, Y. Ilchenko³⁹, D. Iliadis¹⁵⁴, D. Imbault⁷⁸, M. Imhaeuser¹⁷⁴, M. Imori¹⁵⁵, T. Ince²⁰, J. Inigo-Golfin²⁹, P. Ioannou⁸, M. Iodice^{134a}, G. Ionescu⁴, A. Irles Quiles¹⁶⁷, K. Ishii⁶⁶, A. Ishikawa⁶⁷, M. Ishino⁶⁶, R. Ishmukhametov³⁹, T. Isobe¹⁵⁵, C. Issever¹¹⁸, S. Istin^{18a}, Y. Itoh¹⁰¹, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁶, J.M. Izen⁴⁰, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹, V. Jain⁶¹, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jankowski¹⁵⁸, E. Jansen⁷⁷, A. Jantsch⁹⁹, M. Janus²⁰, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, K. Jelen³⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴, H. Ji¹⁷², W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b}, M. Jimenez Belenguer²⁹, G. Jin^{32b}, S. Jin^{32a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶, A. Johnson⁵, K. Jon-And^{146a,146b}, G. Jones⁸², R.W.L. Jones⁷¹, T.W. Jones⁷⁷, T.J. Jones⁷³, O. Jonsson²⁹, K.K. Joo¹⁵⁸, C. Joram²⁹, P.M. Jorge^{124a,b}, J. Joseph¹⁴, X. Ju¹³⁰, V. Juranek¹²⁵, P. Jussel⁶², V.V. Kabachenko¹²⁸, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarzka³⁸, P. Kadlecik³⁵, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, S. Kaiser⁹⁹, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁴, L.V. Kalinovskaya⁶⁵, S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda¹⁵⁵, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁶, B. Kaplan¹⁷⁵, A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁴³, M. Karagoz¹¹⁸, M. Karneveskiy⁴¹, K. Karr⁵, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif⁵⁷, A. Kasmi³⁹, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁷, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁵, S.I. Kazi⁸⁶, J.R. Keates⁸², R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁵, M. Kelly⁸², J. Kennedy⁹⁸, C.J. Kenney¹⁴³, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁴, K. Kessoku¹⁵⁵, C. Ketterer⁴⁸, M. Khakzad²⁸, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁵, A. Khodinov¹⁴⁸, A.G. Kholodenko¹²⁸, A. Khomich^{58a}, T.J. Khoo²⁷, G. Khorauli²⁰, N. Khovanskiy⁶⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁵, J. Khubua⁵¹, G. Kilvington⁷⁶, H. Kim⁷, M.S. Kim², P.C. Kim¹⁴³, S.H. Kim¹⁶⁰, N. Kimura¹⁷⁰, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁷, R.S.B. King¹¹⁸, J. Kirk¹²⁹, G.P. Kirsch¹¹⁸, L.E. Kirsch²², A.E. Kiryunin⁹⁹, D. Kisielewska³⁷, T. Kittelmann¹²³, A.M. Kiver¹²⁸, H. Kiyamura⁶⁷, E. Kladiva^{144b}, J. Klaiber-Lodewigs⁴², M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷¹, A. Klimentov²⁴, R. Klingenberg⁴², E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, E. Kneringer⁶², J. Knobloch²⁹, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, B. Koblitz²⁹, M. Kocian¹⁴³, A. Kocnar¹¹³, P. Kodys¹²⁶, K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, S. König⁴⁸, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁹, E. Koffeman¹⁰⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁶, T. Koi¹⁴³, T. Kokott²⁰, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁵, I. Koletsou^{89a,89b}, J. Koll⁸⁸, D. Kollar²⁹, M. Kollefrath⁴⁸, S.D. Kolya⁸², A.A. Komar⁹⁴, J.R. Komaragiri¹⁴², T. Kondo⁶⁶, T. Kono^{41,p}, A.I. Kononov⁴⁸, R. Konoplich^{108,q}, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁴, S. Koperny³⁷, S.V. Kopikov¹²⁸, K. Korcyl³⁸, K. Kordas¹⁵⁴, V. Koreshev¹²⁸, A. Korn¹⁴, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰, M.J. Kotamäki²⁹, S. Kotov⁹⁹, V.M. Kotov⁶⁵, C. Kourkoumelis⁸, A. Koutsman¹⁰⁵, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, O. Krasel⁴², M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, A. Kreisel¹⁵³, F. Krejci¹²⁷, J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁵, H. Krüger²⁰, Z.V. Krumshteyn⁶⁵, A. Kruth²⁰, T. Kubota¹⁵⁵, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl¹⁷⁴, D. Kuhn⁶², V. Kukhtin⁶⁵, Y. Kulchitsky⁹⁰, S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁸³, N. Kundu¹¹⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁷, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, W. Kuykendall¹³⁸, M. Kuze¹⁵⁷, P. Kuzhir⁹¹, O. Kvasnicka¹²⁵, R. Kwee¹⁵, A. La Rosa²⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁵, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laïsne⁵⁵, M. Lamanna²⁹, C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, H. Landsman¹⁵², J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzscheid²⁹, V.V. Lapin^{128,*}, S. Laplace⁴, C. Lapoire²⁰, J.F. Laporte¹³⁶, T. Lari^{89a}, A.V. Larionov¹²⁸, A. Larner¹¹⁸, C. Lasseur²⁹, M. Lassnig²⁹, W. Lau¹¹⁸, P. Laurelli⁴⁷, A. Lavorato¹¹⁸, W. Lavrijsen¹⁴, P. Laycock⁷³, A.B. Lazarev⁶⁵, A. Lazzaro^{89a,89b}, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹³⁶, M. Leahu²⁹, A. Lebedev⁶⁴, C. Lebel⁹³, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹⁵⁰, S.C. Lee¹⁵¹, L. Lee¹⁷⁵, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, A. Leger⁴⁹, B.C. LeGeyt¹²⁰,

F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, M. Lehto¹³⁹, X. Lei⁶, M.A.L. Leite^{23b}, R. Leitner¹²⁶, D. Lellouch¹⁷¹, J. Lellouch⁷⁸, M. Leltchouk³⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁷⁴, G. Lenzen¹⁷⁴, B. Lenzi¹³⁶, K. Leonhardt⁴³, S. Leontsinis⁹, C. Leroy⁹³, J.-R. Lessard¹⁶⁹, J. Lesser^{146a}, C.G. Lester²⁷, A. Leung Fook Cheong¹⁷², J. Levêque⁸³, D. Levin⁸⁷, L.J. Levinson¹⁷¹, M.S. Levitski¹²⁸, M. Lewandowska²¹, M. Leyton¹⁵, B. Li⁸³, H. Li¹⁷², S. Li^{32b}, X. Li⁸⁷, Z. Liang³⁹, Z. Liang^{118,r}, B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, R. Lifshitz¹⁵², J.N. Lilley¹⁷, A. Limosani⁸⁶, M. Limper⁶³, S.C. Lin^{151,s}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, L. Lipinsky¹²⁵, A. Lipniacka¹³, T.M. Liss¹⁶⁵, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu^{151,t}, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, S. Liu², Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, S. Lockwitz¹⁷⁵, T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁵, C.W. Loh¹⁶⁸, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, J. Loken¹¹⁸, V.P. Lombardo^{89a,89b}, R.E. Long⁷¹, L. Lopes^{124a,b}, D. Lopez Mateos^{34,m}, M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe¹⁴³, F. Lu^{32a}, J. Lu², L. Lu³⁹, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶¹, G. Luijckx¹⁰⁵, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹, A. Lupi^{122a,122b}, G. Lutz⁹⁹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷², M. Maaßen⁴⁸, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a,b}, D. Macina⁴⁹, R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁴, S. Mättig⁴¹, P.J. Magalhaes Martins^{124a,f}, L. Magnoni²⁹, E. Magradze⁵¹, C.A. Magrath¹⁰⁴, Y. Mahalalel¹⁵³, K. Mahboubi⁴⁸, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a}, A. Maio^{124a,l}, S. Majewski²⁴, Y. Makida⁶⁶, N. Makovec¹¹⁵, P. Mal⁶, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶³, D. Malon⁵, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov⁶⁵, R. Mameghani⁹⁸, J. Mamuzic^{12b}, A. Manabe⁶⁶, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangeard⁸⁸, I.D. Manjavidze⁶⁵, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Manz⁹⁹, A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁹, F. Marchese^{133a,133b}, M. Marchesotti²⁹, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, A. Marin^{21,*}, C.P. Marino⁶¹, F. Marroquim^{23a}, R. Marshall⁸², Z. Marshall^{34,m}, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, A.J. Martin¹⁷⁵, B. Martin²⁹, B. Martin⁸⁸, F.F. Martin¹²⁰, J.P. Martin⁹³, Ph. Martin⁵⁵, T.A. Martin¹⁷, B. Martin dit Latour⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷, A.C. Martyniuk⁸², M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, M. Maß⁴², I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, M. Mathes²⁰, P. Matricon¹¹⁵, H. Matsumoto¹⁵⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁷, C. Mattravers^{118,u}, J.M. Maugain²⁹, S.J. Maxfield⁷³, E.N. May⁵, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰, M. Mazzanti^{89a}, E. Mazzoni^{122a,122b}, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶, J.A. Mcfayden¹³⁹, H. McGlone⁵³, G. Mchedlidze⁵¹, R.A. McLaren²⁹, T. McLaughlan¹⁷, S.J. McMahon¹²⁹, T.R. McMahon⁷⁶, T.J. McMahon¹⁷, R.A. McPherson^{169,h}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁴, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase⁴¹, A. Mehta⁷³, K. Meier^{58a}, J. Meinhardt⁴⁸, B. Meirose⁷⁹, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷², L. Mendoza Navas¹⁶², Z. Meng^{151,t}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹, C. Menot²⁹, E. Meoni¹¹, D. Merkl⁹⁸, P. Mermoud¹¹⁸, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰, A. Messina²⁹, J. Metcalfe¹⁰³, A.S. Mete⁶⁴, S. Meuser²⁰, C. Meyer⁸¹, J.-P. Meyer¹³⁶, J. Meyer¹⁷³, J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶⁴, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹, P. Miele²⁹, S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷¹, M. Mikestikova¹²⁵, B. Mikulec⁴⁹, M. Mikuz⁷⁴, D.W. Miller¹⁴³, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, D. Milstein¹⁷¹, A.A. Minaenko¹²⁸, M. Miñano¹⁶⁷, I.A. Minashvili⁶⁵, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁵, Y. Ming¹³⁰, L.M. Mir¹¹, G. Mirabelli^{132a}, L. Miralles Verge¹¹, A. Misiejuk⁷⁶, A. Mitra¹¹⁸, J. Mitrevski¹³⁷, G.Y. Mitrofanov¹²⁸, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁶, P.S. Miyagawa⁸², K. Miyazaki⁶⁷, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, P. Mockett¹³⁸, S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸, B. Mohn¹³, W. Mohr⁴⁸, S. Mohr dieck-Möck⁹⁹, A.M. Moiseev^{128,*}, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, L. Moneta⁴⁹, J. Monk⁷⁷, E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, A. Morais^{124a,b}, N. Morange¹³⁶,

J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹, M. Moreno Llácer¹⁶⁷, P. Morettini^{50a}, M. Morii⁵⁷, J. Morin⁷⁵, Y. Morita⁶⁶, A.K. Morley²⁹, G. Mornacchi²⁹, M.-C. Morone⁴⁹, J.D. Morris⁷⁵, H.G. Moser⁹⁹, M. Mosidze⁵¹, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha⁹, S.V. Mouraviev⁹⁴, E.J.W. Moyse⁸⁴, M. Mudrinic^{12b}, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰, T.A. Müller⁹⁸, D. Muenstermann⁴², A. Muijs¹⁰⁵, A. Muir¹⁶⁸, Y. Munwes¹⁵³, K. Murakami⁶⁶, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁶, Y. Nagasaka⁶⁰, A.M. Nairz²⁹, Y. Nakahama¹¹⁵, K. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, M. Nash^{77,u}, I. Nasteva⁸², N.R. Nation²¹, T. Nattermann²⁰, T. Naumann⁴¹, G. Navarro¹⁶², H.A. Neal⁸⁷, E. Nebot⁸⁰, P.Yu. Nechaeva⁹⁴, A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹, A. Nelson⁶⁴, S. Nelson¹⁴³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi²⁹, S.Y. Nesterov¹²¹, M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, T. Niinikoski²⁹, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, K. Nikolaev⁶⁵, I. Nikolic-Audit⁷⁸, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁷, R. Nisius⁹⁹, L. Nodulman⁵, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, H. Nomoto¹⁵⁵, M. Nordberg²⁹, B. Nordkvist^{146a,146b}, O. Norriella Francisco¹¹, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁶, M. Nožička⁴¹, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger²⁰, T. Nunnemann⁹⁸, E. Nurse⁷⁷, T. Nyman²⁹, B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, F.G. Oakham^{28,d}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁷, S. Oda¹⁵⁵, S. Odaka⁶⁶, J. Odier⁸³, G.A. Odino^{50a,50b}, H. Ogren⁶¹, A. Oh⁸², S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, H. Ohshita¹⁴⁰, T.K. Ohsaka⁶⁶, T. Ohsugi⁵⁹, S. Okada⁶⁷, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵, M. Olcese^{50a}, A.G. Olchevski⁶⁵, M. Oliveira^{124a,f}, D. Oliveira Damazio²⁴, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, C. Omachi⁶⁷, A. Onofre^{124a,v}, P.U.E. Onyisi³⁰, C.J. Oram^{159a}, G. Ordonez¹⁰⁴, M.J. Oreglia³⁰, F. Orellana⁴⁹, Y. Oren¹⁵³, D. Orestano^{134a,134b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, E.O. Ortega¹³⁰, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135c}, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a}, M. Owen⁸², S. Owen¹³⁹, A. Oyarzun^{31b}, O.K. Øye¹³, V.E. Ozcan⁷⁷, N. Ozturk⁷, A. Pacheco Pages¹¹, C. Padilla Aranda¹¹, E. Paganis¹³⁹, F. Paige²⁴, K. Pajchel¹¹⁷, S. Palestini²⁹, D. Pallin³³, A. Palma^{124a,b}, J.D. Palmer¹⁷, Y.B. Pan¹⁷², E. Panagiotopoulou⁹, B. Panes^{31a}, N. Panikashvili⁸⁷, S. Panitkin²⁴, D. Pantea^{25a}, M. Panuskova¹²⁵, V. Paolone¹²³, A. Paoloni^{133a,133b}, A. Papadelis^{146a}, Th.D. Papadopoulou⁹, A. Paramonov⁵, S.J. Park⁵⁴, W. Park^{24,w}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸, E. Pasqualucci^{132a}, A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore²⁹, G. Pásztor^{49,x}, S. Pataria¹⁷², N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsny^{144a}, M.I. Pedraza Morales¹⁷², S.V. Peleganchuk¹⁰⁷, H. Peng¹⁷², R. Pengo²⁹, A. Penson³⁴, J. Penwell⁶¹, M. Perantoni^{23a}, K. Perez^{34,m}, T. Perez Cavalcanti⁴¹, E. Perez Codina¹¹, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, I. Peric²⁰, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴, S. Persebe^{3a}, P. Perus¹¹⁵, V.D. Peshekhonov⁶⁵, O. Peters¹⁰⁵, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁸³, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, A. Phan⁸⁶, A.W. Phillips²⁷, P.W. Phillips¹²⁹, G. Piacquadio²⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b}, A. Pickford⁵³, R. Piegaia²⁶, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,l}, M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold², J. Ping^{32c}, B. Pinto^{124a,b}, O. Pirotte²⁹, C. Pizio^{89a,89b}, R. Placakyte⁴¹, M. Plamondon¹⁶⁹, W.G. Plano⁸², M.-A. Pleier²⁴, A.V. Pleskach¹²⁸, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³, L. Poggioli¹¹⁵, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio¹³⁸, A. Polini^{19a}, J. Poll⁷⁵, V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso⁴⁸, R. Porter¹⁶³, C. Posch²¹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter⁸⁵, G. Poulard²⁹, J. Poveda¹⁷², R. Prabhu⁷⁷, P. Pralavorio⁸³, S. Prasad⁵⁷, R. Pravahan⁷, S. Prell⁶⁴, K. Pretzl¹⁶, L. Pribyl²⁹, D. Price⁶¹, L.E. Price⁵, M.J. Price²⁹, P.M. Prichard⁷³, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev²⁹, F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³, H. Przysiezniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴, J. Purdham⁸⁷, M. Purohit^{24,w}, P. Puze¹¹⁵, Y. Pylypchenko¹¹⁷, J. Qian⁸⁷, Z. Qian⁸³, Z. Qin⁴¹, A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷², F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radescu^{58b}, B. Radics²⁰, T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁷, A.M. Rahimi¹⁰⁹, S. Rajagopalan²⁴, S. Rajek⁴², M. Rammensee⁴⁸, M. Rammes¹⁴¹, M. Ramstedt^{146a,146b},

K. Randrianarivony²⁸, P.N. Ratoff⁷¹, F. Rauscher⁹⁸, E. Rauter⁹⁹, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b}, A. Redelbach¹⁷³, G. Redlinger²⁴, R. Reece¹²⁰, K. Reeves⁴⁰, A. Reichold¹⁰⁵, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², D. Reljic^{12a}, C. Rembser²⁹, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, P. Renkel³⁹, B. Rensch³⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, A. Richards⁷⁷, R. Richter⁹⁹, E. Richter-Was^{38,y}, M. Ridel⁷⁸, S. Rieke⁸¹, M. Rijpsstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,h}, A. Robichaud-Veronneau⁴⁹, D. Robinson²⁷, J.E.M. Robinson⁷⁷, M. Robinson¹¹⁴, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, S. Rodier⁸⁰, D. Rodriguez¹⁶², Y. Rodriguez Garcia¹⁵, A. Roe⁵⁴, S. Roe²⁹, O. Røhne¹¹⁷, V. Rojo¹, S. Rolli¹⁶¹, A. Romanouk⁹⁶, V.M. Romanov⁶⁵, G. Romeo²⁶, D. Romero Maltrana^{31a}, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati¹³⁸, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶⁴, P.L. Rosendahl¹³, L. Rossetlet⁴⁹, V. Rossetti¹¹, E. Rossi^{102a,102b}, L.P. Rossi^{50a}, L. Rossi^{89a,89b}, M. Rotaru^{25a}, I. Roth¹⁷¹, J. Rothberg¹³⁸, I. Rottländer²⁰, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan¹¹⁵, I. Rubinskiy⁴¹, B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, G. Rudolph⁶², F. Rühr⁶, A. Ruiz-Martinez⁶⁴, E. Rulikowska-Zarebska³⁷, V. Rumiantsev^{91,*}, L. Rummyantsev⁶⁵, K. Runge⁴⁸, O. Runolfsson²⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵, D.R. Rust⁶¹, J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, V. Ryadovikov¹²⁸, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, S. Rzaeva¹⁰, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁵, F. Safai Tehrani^{132a,132b}, H. Sakamoto¹⁵⁵, G. Salamanna¹⁰⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salzburger²⁹, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁴, P. Sandhu¹⁵⁸, T. Sandoval²⁷, R. Sandstroem¹⁰⁵, S. Sandvoss¹⁷⁴, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a,l}, T. Sarangi¹⁷², E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁴, O. Sasaki⁶⁶, T. Sasaki⁶⁶, N. Sasao⁶⁸, I. Satsounkevitch⁹⁰, G. Sauvage⁴, J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³, P. Savva⁹, L. Sawyer^{24,i}, D.H. Saxon⁵³, L.P. Says³³, C. Sbarra^{19a,19b}, A. Sbrizzi^{19a,19b}, O. Scallan⁹³, D.A. Scannicchio¹⁶³, J. Schaarschmidt⁴³, P. Schacht⁹⁹, U. Schäfer⁸¹, S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M.I. Scherzer¹⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{36a,36b}, S. Schlenker²⁹, J.L. Schlereth⁵, E. Schmidt⁴⁸, M.P. Schmidt^{175,*}, K. Schmieden²⁰, C. Schmitt⁸¹, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹, D. Schouten¹⁴², J. Schovancova¹²⁵, M. Schram⁸⁵, A. Schreiner⁶³, C. Schroeder⁸¹, N. Schroer^{58c}, S. Schuh²⁹, G. Schuler²⁹, J. Schultes¹⁷⁴, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³, J. Schwindling¹³⁶, W.G. Scott¹²⁹, J. Searcy¹¹⁴, E. Sedykh¹²¹, E. Segura¹¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, R. Seuster⁹⁹, H. Severini¹¹¹, M.E. Sevir⁸⁶, A. Sfyrila²⁹, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵, L. Shaver⁶, C. Shaw⁵³, K. Shaw^{164a,164c}, D. Sherman¹⁷⁵, P. Sherwood⁷⁷, A. Shibata¹⁰⁸, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, A. Shmeleva⁹⁴, M.J. Shochet³⁰, D. Short¹¹⁸, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti¹⁵, A. Siebel¹⁷⁴, F. Siegert⁴⁸, J. Siegrist¹⁴, Dj. Sijacki^{12a}, O. Silbert¹⁷¹, J. Silva^{124a,z}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, M. Simonyan³⁵, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa⁸¹, A.N. Sisakyan⁶⁵, S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjrursen¹³, L.A. Skinnari¹⁴, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, N. Skvorodnev²², M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, T.J. Sloan⁷¹, J. Sloper²⁹, V. Smakhtin¹⁷¹, S.Yu. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, J. Snuverink¹⁰⁵, S. Snyder²⁴, M. Soares^{124a}, R. Sobie^{169,h}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, J. Sondericker²⁴, N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sorbi^{89a,89b}, M. Sosebee⁷, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò³⁴, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, E. Spiriti^{134a}, R. Spiwoks²⁹, M. Spousta¹²⁶, T. Spreitzer¹⁵⁸, B. Spurlock⁷, R.D. St. Denis⁵³, T. Stahl¹⁴¹, J. Stahlman¹²⁰, R. Stamen^{58a},

E. Stanecka²⁹, R.W. Stanek⁵, C. Stancu^{134a}, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁹¹, A. Staude⁹⁸, P. Stavina^{144a}, G. Stavropoulos¹⁴, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁴¹, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², K. Stevenson⁷⁵, G.A. Stewart⁵³, T. Stockmanns²⁰, M.C. Stockton²⁹, K. Stoerig⁴⁸, G. Stoica^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg⁸⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷³, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹, J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁴, D.A. Soh^{151,r}, D. Su¹⁴³, S. Subramania², Y. Sugaya¹¹⁶, T. Sugimoto¹⁰¹, C. Suhr¹⁰⁶, K. Suita⁶⁷, M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{3d}, T. Sumida²⁹, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz^{164a,164b}, S. Sushkov¹¹, G. Susinno^{36a,36b}, M.R. Sutton¹³⁹, Y. Suzuki⁶⁶, Yu.M. Sviridov¹²⁸, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶, B. Szeless²⁹, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann²⁹, A. Taffard¹⁶³, R. Tafiout^{159a}, A. Taga¹¹⁷, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁴, R. Takashima⁶⁹, H. Takeda⁶⁷, T. Takeshita¹⁴⁰, M. Talby⁸³, A. Talyshev¹⁰⁷, M.C. Tamssett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁶, Y. Tanaka¹⁰⁰, K. Tani⁶⁷, N. Tannoury⁸³, G.P. Tappern²⁹, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁴, G.F. Tartarelli^{89a}, P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, C. Taylor⁷⁷, F.E. Taylor⁹², G. Taylor¹³⁷, G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, Y.D. Tennenbaum-Katan¹⁵², S. Terada⁶⁶, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Terwort^{41,p}, M. Testa⁴⁷, R.J. Teuscher^{158,h}, C.M. Tevlin⁸², J. Thadome¹⁷⁴, J. Therhaag²⁰, T. Theveniaux-Pelzer⁷⁸, M. Thioye¹⁷⁵, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson⁸⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, E. Thomson¹²⁰, M. Thomson²⁷, R.P. Thun⁸⁷, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov¹⁰⁷, C.J.W.P. Timmermans¹⁰⁴, P. Tipton¹⁷⁵, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, J. Tobias⁴⁸, B. Toczec³⁷, T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁶, S. Tokár^{144a}, K. Tokunaga⁶⁷, K. Tokushuku⁶⁶, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins¹⁴, K. Toms¹⁰³, A. Tonazzo^{134a,134b}, G. Tong^{32a}, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁵, I. Torchiani²⁹, E. Torrence¹¹⁴, E. Torró Pastor¹⁶⁷, J. Toth^{83,x}, F. Touchard⁸³, D.R. Tovey¹³⁹, D. Traynor⁷⁵, T. Trefzger¹⁷³, J. Treis²⁰, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvoid⁷⁸, T.N. Trinh⁷⁸, M.F. Tripiana⁷⁰, N. Triplett⁶⁴, W. Trischuk¹⁵⁸, A. Trivedi^{24,w}, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trottier-McDonald¹⁴², A. Trzupek³⁸, C. Tsarouchas²⁹, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehsha⁹⁰, D. Tsionou⁴, G. Tsipolitis⁹, V. Tsiskaridze⁴⁸, E.G. Tskhadadze⁵¹, I.I. Tsukerman⁹⁵, V. Tsulaia¹²³, J.-W. Tsung²⁰, S. Tsuno⁶⁶, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, P.M. Tuts³⁴, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, D. Typaldos¹⁷, H. Tyrvalinen²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, D.G. Underwood⁵, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁶, D. Urbaniec³⁴, E. Urkovsky¹⁵³, P. Urquijo⁴⁹, P. Urrejola^{31a}, G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, C. Valderanis⁹⁹, J. Valenta¹²⁵, P. Valente^{132a}, S. Valentini^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster²⁹, B. Van Eijk¹⁰⁵, N. van Eldik⁸⁴, P. van Gemmeren⁵, Z. van Kesteren¹⁰⁵, I. van Vulpen¹⁰⁵, W. Vandelli²⁹, G. Vandoni²⁹, A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, F. Varela Rodriguez²⁹, R. Vari^{132a}, E.W. Varnes⁶, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, C. Vellidis⁸, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura¹³⁸, S. Ventura⁴⁷, M. Venturi⁴⁸, N. Venturi¹⁶, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴³, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵, T. Vickey^{145b,aa}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vinciter²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁵, M. Virchaux^{136,*}, S. Viret³³, J. Virzi¹⁴, A. Vitale^{19a,19b}, O. Vitells¹⁷¹, I. Vivarelli⁴⁸, F. Vives Vaque¹¹, S. Vlachos⁹, M. Vlasak¹²⁷, N. Vlasov²⁰, A. Vogel²⁰, P. Vokac¹²⁷, M. Volpi¹¹, G. Volpini^{89a}, H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶, A.P. Vorobiev¹²⁸, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁴, J.H. Vosseveld⁷³, A.S. Vovenko¹²⁸, N. Vranjes^{12a}, M. Vranjes Milosavljevic^{12a}, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁸¹, R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁴, P. Wagner¹²⁰, H. Wahlen¹⁷⁴, J. Wakabayashi¹⁰¹, J. Walbersloh⁴², S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁵, P. Waller⁷³, C. Wang⁴⁴,

H. Wang¹⁷², J. Wang¹⁵¹, J. Wang^{32d}, J.C. Wang¹³⁸, R. Wang¹⁰³, S.M. Wang¹⁵¹, A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸, P.M. Watkins¹⁷, A.T. Watson¹⁷, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, J. Weber⁴², M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²², P.S. Wells²⁹, M. Wen⁴⁷, T. Wenaus²⁴, S. Wendler¹²³, Z. Weng^{151,r}, T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, M. Wessels^{58a}, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, S.P. Whitaker²¹, A. White⁷, M.J. White⁸⁶, S. White²⁴, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶¹, F. Wicek¹¹⁵, D. Wicke¹⁷⁴, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷², M. Wielers¹²⁹, P. Wienemann²⁰, C. Wigglesworth⁷³, L.A.M. Wiik⁴⁸, A. Wildauer¹⁶⁷, M.A. Wildt^{41,p}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸, H. Wolters^{124a,f}, G. Wooden¹¹⁸, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸⁴, K. Wraight⁵³, C. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷², X. Wu⁴⁹, Y. Wu^{32b}, E. Wulf³⁴, R. Wunstorf⁴², B.M. Wynne⁴⁵, L. Xaplanteris⁹, S. Xella³⁵, S. Xie⁴⁸, Y. Xie^{32a}, C. Xu^{32b}, D. Xu¹³⁹, G. Xu^{32a}, B. Yabsley¹⁵⁰, M. Yamada⁶⁶, A. Yamamoto⁶⁶, K. Yamamoto⁶⁴, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁷, Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶¹, Y. Yang^{32a}, Z. Yang^{146a,146b}, S. Yanush⁹¹, W.-M. Yao¹⁴, Y. Yao¹⁴, Y. Yasu⁶⁶, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷⁰, R. Yoshida⁵, C. Young¹⁴³, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu^{32c,ab}, L. Yuan^{32a,ac}, A. Yurkewicz¹⁴⁸, V.G. Zaets¹²⁸, R. Zaidan⁶³, A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, Yo.K. Zalite¹²¹, L. Zanello^{132a,132b}, P. Zarzhitsky³⁹, A. Zaytsev¹⁰⁷, M. Zdrzil¹⁴, C. Zeitnitz¹⁷⁴, M. Zeller¹⁷⁵, P.F. Zema²⁹, A. Zemla³⁸, C. Zendler²⁰, A.V. Zenin¹²⁸, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zenonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁵, S. Zheng^{32a}, J. Zhong^{151,ad}, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹, Y. Zhu¹⁷², X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶¹, B. Zilka^{144a}, R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷², A. Zoccoli^{19a,19b}, Y. Zolnierowski⁴, A. Zsenei²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalinski²⁹

¹ University at Albany, 1400 Washington Ave, Albany, NY 12222, United States

² University of Alberta, Department of Physics, Centre for Particle Physics, Edmonton, AB T6G 2G7, Canada

³ Ankara University^(a), Faculty of Sciences, Department of Physics, TR 061000 Tandogan, Ankara; Dumlupinar University^(b), Faculty of Arts and Sciences, Department of Physics, Kutahya; Gazi University^(c), Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara; TOBB University of Economics and Technology^(d), Faculty of Arts and Sciences, Division of Physics, 06560, Sogutozu, Ankara; Turkish Atomic Energy Authority^(e), 06530, Lodumlu, Ankara, Turkey

⁴ LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

⁵ Argonne National Laboratory, High Energy Physics Division, 9700 S. Cass Avenue, Argonne, IL 60439, United States

⁶ University of Arizona, Department of Physics, Tucson, AZ 85721, United States

⁷ The University of Texas at Arlington, Department of Physics, Box 19059, Arlington, TX 76019, United States

⁸ University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopoli, Zografou, GR 15771 Athens, Greece

⁹ National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780 Zografou, Greece

¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan

¹¹ Institut de Física d'Altes Energies, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES-08193 Bellaterra (Barcelona), Spain

¹² University of Belgrade^(a), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences^(b), M. Petrovica Alasa 12-14, 11001 Belgrade, Serbia

¹³ University of Bergen, Department for Physics and Technology, Allegaten 55, NO-5007 Bergen, Norway

¹⁴ Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States

¹⁵ Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany

¹⁶ University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH-3012 Bern, Switzerland

¹⁷ University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom

¹⁸ Bogazici University^(a), Faculty of Sciences, Department of Physics, TR-80815 Bebek-Istanbul; Dogus University^(b), Faculty of Arts and Sciences, Department of Physics, 34722 Kadikoy, Istanbul; Gaziantep University^(c), Faculty of Engineering, Department of Physics Engineering, 27310 Sehitkamil, Gaziantep; Istanbul Technical University^(d), Faculty of Arts and Sciences, Department of Physics, 34469 Maslak, Istanbul, Turkey

¹⁹ INFN Sezione di Bologna^(a); Università di Bologna, Dipartimento di Fisica^(a), viale C. Berti Pichat, 6/2, IT-40127 Bologna, Italy

²⁰ University of Bonn, Physikalisches Institut, Nussallee 12, D-53115 Bonn, Germany

²¹ Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States

²² Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States

²³ Universidade Federal do Rio De Janeiro, COPPE/EE/IF^(a), Caixa Postal 68528, Ilha do Fundao, BR-21945-970 Rio de Janeiro; Universidade de Sao Paulo^(b), Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo, SP 05508-900, Brazil

²⁴ Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States

²⁵ National Institute of Physics and Nuclear Engineering^(a), Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125; University Politehnica Bucharest^(b), Rectorat, AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University^(c) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania

²⁶ Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I, C. Universitaria, 1428 Buenos Aires, Argentina

²⁷ University of Cambridge, Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

²⁸ Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada

²⁹ CERN, CH-1211 Geneva 23, Switzerland

³⁰ University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States

- ³¹ Pontificia Universidad Católica de Chile, Facultad de Física, Departamento de Física^(a), Avda. Vicuña Mackenna 4860, San Joaquín, Santiago; Universidad Técnica Federico Santa María, Departamento de Física^(b), Avda. España 1680, Casilla 110-V, Valparaíso, Chile
- ³² Institute of High Energy Physics, Chinese Academy of Sciences^(a), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN, Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics^(b), Hefei, CN, Anhui 230026; Nanjing University, Department of Physics^(c), Nanjing, CN, Jiangsu 210093; Shandong University, High Energy Physics Group^(d), Jinan, CN, Shandong 250100, China
- ³³ Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR-63177 Aubière Cedex, France
- ³⁴ Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States
- ³⁵ University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK-2100 København Ø, Denmark
- ³⁶ INFN Gruppo Collegato di Cosenza^(a); Università della Calabria, Dipartimento di Fisica^(b), IT-87036 Arcavacata di Rende, Italy
- ³⁷ Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL-31342 Kraków, Poland
- ³⁹ Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States
- ⁴⁰ University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States
- ⁴¹ DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
- ⁴² TU Dortmund, Experimentelle Physik IV, DE-44221 Dortmund, Germany
- ⁴³ Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
- ⁴⁴ Duke University, Department of Physics, Durham, NC 27708, United States
- ⁴⁵ University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt; Johannes Gutenbergstrasse 3 AT-2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, via Enrico Fermi 40, IT-00044 Frascati, Italy
- ⁴⁸ Albert-Ludwigs-Universität, Fakultät für Mathematik und Physik, Hermann-Herder Str. 3, D-79104 Freiburg i.Br., Germany
- ⁴⁹ Université de Genève, Section de Physique, 24 rue Ernest Ansermet, CH-1211 Genève 4, Switzerland
- ⁵⁰ INFN Sezione di Genova^(a); Università di Genova, Dipartimento di Fisica^(b), via Dodecaneso 33, IT-16146 Genova, Italy
- ⁵¹ Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili St., GE-380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE-380086 Tbilisi, Georgia
- ⁵² Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany
- ⁵³ University of Glasgow, Department of Physics and Astronomy, Glasgow G12 8QQ, United Kingdom
- ⁵⁴ Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany
- ⁵⁵ LPSC, CNRS/IN2P3 and Univ. Joseph Fourier Grenoble, 53 avenue des Martyrs, FR-38026 Grenoble Cedex, France
- ⁵⁶ Hampton University, Department of Physics, Hampton, VA 23668, United States
- ⁵⁷ Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, MA 02138, United States
- ⁵⁸ Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik^(a), Im Neuenheimer Feld 227, D-69120 Heidelberg; Physikalisches Institut^(b), Philosophenweg 12, D-69120 Heidelberg; ZITI Ruprecht-Karls-Universität Heidelberg^(c), Lehrstuhl für Informatik V, B6, 23-29, D-68131 Mannheim, Germany
- ⁵⁹ Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP, Hiroshima 739-8526, Japan
- ⁶⁰ Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP, Hiroshima 731-5193, Japan
- ⁶¹ Indiana University, Department of Physics, Swain Hall West 117, Bloomington, IN 47405-7105, United States
- ⁶² Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A-6020 Innsbruck, Austria
- ⁶³ University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242-1479, United States
- ⁶⁴ Iowa State University, Department of Physics and Astronomy, Ames High Energy Physics Group, Ames, IA 50011-3160, United States
- ⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, RU-141980 Moscow Region, Russia
- ⁶⁶ KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan
- ⁶⁷ Kobe University, Graduate School of Science, 1-1 Rokkodai-cho, Nada-ku, JP, Kobe 657-8501, Japan
- ⁶⁸ Kyoto University, Faculty of Science, Oiwake-cho, Kitashirakawa, Sakyo-shi, JP, Kyoto 606-8502, Japan
- ⁶⁹ Kyoto University of Education, 1 Fukakusa, Fushimi-ku, Kyoto-shi, JP, Kyoto 612-8522, Japan
- ⁷⁰ Universidad Nacional de La Plata, FCE, Departamento de Física, IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina
- ⁷¹ Lancaster University, Physics Department, Lancaster LA1 4YB, United Kingdom
- ⁷² INFN Sezione di Lecce^(a); Università del Salento, Dipartimento di Fisica^(b), Via Arnesano, IT-73100 Lecce, Italy
- ⁷³ University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, United Kingdom
- ⁷⁴ Jožef Stefan Institute and University of Ljubljana, Department of Physics, SI-1000 Ljubljana, Slovenia
- ⁷⁵ Queen Mary University of London, Department of Physics, Mile End Road, London E1 4NS, United Kingdom
- ⁷⁶ Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom
- ⁷⁷ University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR-75252 Paris Cedex 05, France
- ⁷⁹ Fysiska institutionen, Lunds universitet, Box 118, SE-221 00 Lund, Sweden
- ⁸⁰ Universidad Autónoma de Madrid, Facultad de Ciencias, Departamento de Física Teórica, ES-28049 Madrid, Spain
- ⁸¹ Universität Mainz, Institut für Physik, Staudinger Weg 7, DE-55099 Mainz, Germany
- ⁸² University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ⁸⁴ University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States
- ⁸⁵ McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada
- ⁸⁶ University of Melbourne, School of Physics, AU-Parkville, Victoria 3010, Australia
- ⁸⁷ The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States
- ⁸⁸ Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States
- ⁸⁹ INFN Sezione di Milano^(a); Università di Milano, Dipartimento di Fisica^(b), via Celoria 16, IT-20133 Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Belarus
- ⁹¹ National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Belarus
- ⁹² Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States
- ⁹³ University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU-117 924 Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia
- ⁹⁶ Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU-115409 Moscow, Russia
- ⁹⁷ Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskies gory, GSP-1, Moscow 119991, Russia
- ⁹⁸ Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE-85748 Garching, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, 536 Aba-machi, JP, Nagasaki 851-0193, Japan
- ¹⁰¹ Nagoya University, Graduate School of Science, Furo-cho, Chikusa-ku, Nagoya, 464-8602, Japan
- ¹⁰² INFN Sezione di Napoli^(a); Università di Napoli, Dipartimento di Scienze Fisiche^(b), Complesso Universitario di Monte Sant'Angelo, via Cintia, IT-80126 Napoli, Italy
- ¹⁰³ University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131, United States
- ¹⁰⁴ Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands

- ¹⁰⁵ Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States
- ¹⁰⁷ Budker Institute of Nuclear Physics (BINP), RU-Novosibirsk 630 090, Russia
- ¹⁰⁸ New York University, Department of Physics, 4 Washington Place, New York, NY 10003, United States
- ¹⁰⁹ Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States
- ¹¹⁰ Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan
- ¹¹¹ University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States
- ¹¹² Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States
- ¹¹³ Palacký University, 17.lisťopadu 50a, 772 07 Olomouc, Czech Republic
- ¹¹⁴ University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States
- ¹¹⁵ LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France
- ¹¹⁶ Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan
- ¹¹⁷ University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO-0316 Oslo 3, Norway
- ¹¹⁸ Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
- ¹¹⁹ INFN Sezione di Pavia^(a); Università di Pavia, Dipartimento di Fisica Nucleare e Teorica^(b), Via Bassi 6, IT-27100 Pavia, Italy
- ¹²⁰ University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States
- ¹²¹ Petersburg Nuclear Physics Institute, RU-188 300 Gatchina, Russia
- ¹²² INFN Sezione di Pisa^(a); Università di Pisa, Dipartimento di Fisica E. Fermi^(b), Largo B. Pontecorvo 3, IT-56127 Pisa, Italy
- ¹²³ University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, PA 15260, United States
- ¹²⁴ Laboratorio de Instrumentacao e Fisica Experimental de Partículas – LIP^(a), Avenida Elias Garcia 14-1, PT-1000-149 Lisboa; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE^(b), E-18071 Granada, Spain
- ¹²⁵ Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ-18221 Praha 8, Czech Republic
- ¹²⁶ Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2, CZ-18000 Praha 8, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Zikova 4, CZ-166 35 Praha 6, Czech Republic
- ¹²⁸ State Research Center Institute for High Energy Physics, Moscow Region, 142281, Protvino, Pobeda street, 1, Russia
- ¹²⁹ Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
- ¹³⁰ University of Regina, Physics Department, Canada
- ¹³¹ Ritsumeikan University, Noji Higashi 1 chome 1-1, JP, Kusatsu, Shiga 525-8577, Japan
- ¹³² INFN Sezione di Roma I^(a); Università La Sapienza, Dipartimento di Fisica^(b), Piazzale A. Moro 2, IT-00185 Roma, Italy
- ¹³³ INFN Sezione di Roma Tor Vergata^(a); Università di Roma Tor Vergata, Dipartimento di Fisica^(b), via della Ricerca Scientifica, IT-00133 Roma, Italy
- ¹³⁴ INFN Sezione di Roma Tre^(a); Università Roma Tre, Dipartimento di Fisica^(b), via della Vasca Navale 84, IT-00146 Roma, Italy
- ¹³⁵ Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II, Faculté des Sciences Ain Chock^(a), B.P. 5366, MA, Casablanca; Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN)^(b), B.P. 1382 R.P. 10001, Rabat 10001; Université Mohamed Premier^(c), LPTPM, Faculté des Sciences, B.P. 717, Bd. Mohamed VI, 60000 Oujda; Université Mohammed V, Faculté des Sciences^(d), 4 Avenue Ibn Battouta, B.P. 1014 R.P. 10000 Rabat, Morocco
- ¹³⁶ CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR-91191 Gif-sur-Yvette, France
- ¹³⁷ University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, CA 95064, United States
- ¹³⁸ University of Washington, Seattle, Department of Physics, Box 351560, Seattle, WA 98195-1560, United States
- ¹³⁹ University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom
- ¹⁴⁰ Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP, Nagano 390-8621, Japan
- ¹⁴¹ Universität Siegen, Fachbereich Physik, D 57068 Siegen, Germany
- ¹⁴² Simon Fraser University, Department of Physics, 8888 University Drive, CA-Burnaby, BC V5A 1S6, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford, CA 94309, United States
- ¹⁴⁴ Comenius University, Faculty of Mathematics, Physics & Informatics^(a), Mlynska dolina F2, SK-84248 Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics^(b), Watsonova 47, SK-04353 Kosice, Slovak Republic
- ¹⁴⁵ (a) University of Johannesburg, Department of Physics, P.O. Box 524, Auckland Park, Johannesburg 2006; (b) School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa
- ¹⁴⁶ Stockholm University, Department of Physics^(a); The Oskar Klein Centre^(b), AlbaNova, SE-106 91 Stockholm, Sweden
- ¹⁴⁷ Royal Institute of Technology (KTH), Physics Department, SE-106 91 Stockholm, Sweden
- ¹⁴⁸ Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States
- ¹⁴⁹ University of Sussex, Department of Physics and Astronomy Pevensley 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
- ¹⁵⁰ University of Sydney, School of Physics, AU-Sydney NSW 2006, Australia
- ¹⁵¹ Institute of Physics, Academia Sinica, TW-Taipei 11529, Taiwan
- ¹⁵² Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL-Haifa 32000, Israel
- ¹⁵³ Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL-Tel Aviv 69978, Israel
- ¹⁵⁴ Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR-54124, Thessaloniki, Greece
- ¹⁵⁵ The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP, Tokyo 113-0033, Japan
- ¹⁵⁶ Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
- ¹⁵⁷ Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
- ¹⁵⁸ University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
- ¹⁵⁹ TRIUMF^(a), 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; York University^(b), Department of Physics and Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada
- ¹⁶⁰ University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP, Ibaraki 305-8571, Japan
- ¹⁶¹ Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States
- ¹⁶² Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
- ¹⁶³ University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States
- ¹⁶⁴ INFN Gruppo Collegato di Udine^(a); ICTP^(b), Strada Costiera 11, IT-34014 Trieste; Università di Udine, Dipartimento di Fisica^(c), via delle Scienze 208, IT-33100 Udine, Italy
- ¹⁶⁵ University of Illinois, Department of Physics, 1110 West Green Street, Urbana, IL 61801, United States
- ¹⁶⁶ University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE-751 20 Uppsala, Sweden
- ¹⁶⁷ Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona (IMB-CNM-CSIC) 08193 Bellaterra, Spain
- ¹⁶⁸ University of British Columbia, Department of Physics, 6224 Agricultural Road, CA-Vancouver, B.C. V6T 1Z1, Canada
- ¹⁶⁹ University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada
- ¹⁷⁰ Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
- ¹⁷¹ The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL-76100 Rehovot, Israel
- ¹⁷² University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, WI, United States
- ¹⁷³ Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany
- ¹⁷⁴ Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D-42097 Wuppertal, Germany
- ¹⁷⁵ Yale University, Department of Physics, PO Box 208121, New Haven, CT, 06520-8121, United States
- ¹⁷⁶ Yerevan Physics Institute, Alikhanian Brothers Street 2, AM-375036 Yerevan, Armenia
- ¹⁷⁷ Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France

- ^a Also at LIP, Portugal.
- ^b Also at Faculdade de Ciencias, Universidade de Lisboa, Portugal.
- ^c Also at CPPM, Marseille, France.
- ^d Also at TRIUMF, Vancouver, Canada.
- ^e Also at FPACS, AGH-UST, Cracow, Poland.
- ^f Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
- ^g Also at Università di Napoli Parthenope, Napoli, Italy.
- ^h Also at Institute of Particle Physics (IPP), Canada.
- ⁱ Also at Louisiana Tech University, Ruston, United States.
- ^j Also at Universidade de Lisboa, Lisboa, Portugal.
- ^k At California State University, Fresno, United States.
- ^l Also at Faculdade de Ciencias, Universidade de Lisboa and at Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa, Portugal.
- ^m Also at California Institute of Technology, Pasadena, United States.
- ⁿ Also at University of Montreal, Montreal, Canada.
- ^o Also at Baku Institute of Physics, Baku, Azerbaijan.
- ^p Also at Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany.
- ^q Also at Manhattan College, New York, United States.
- ^r Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^s Also at Taiwan Tier-1, ASGC, Academia Sinica, Taipei, Taiwan.
- ^t Also at School of Physics, Shandong University, Jinan, China.
- ^u Also at Rutherford Appleton Laboratory, Didcot, UK.
- ^v Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
- ^w Also at Department of Physics and Astronomy, University of South Carolina, Columbia, United States.
- ^x Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ^y Also at Institute of Physics, Jagiellonian University, Cracow, Poland.
- ^z Also at Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa, Portugal.
- ^{aa} Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- ^{ab} Also at CEA, Gif sur Yvette, France.
- ^{ac} Also at LPNHE, Paris, France.
- ^{ad} Also at Nanjing University, Nanjing Jiangsu, China.
- * Deceased.